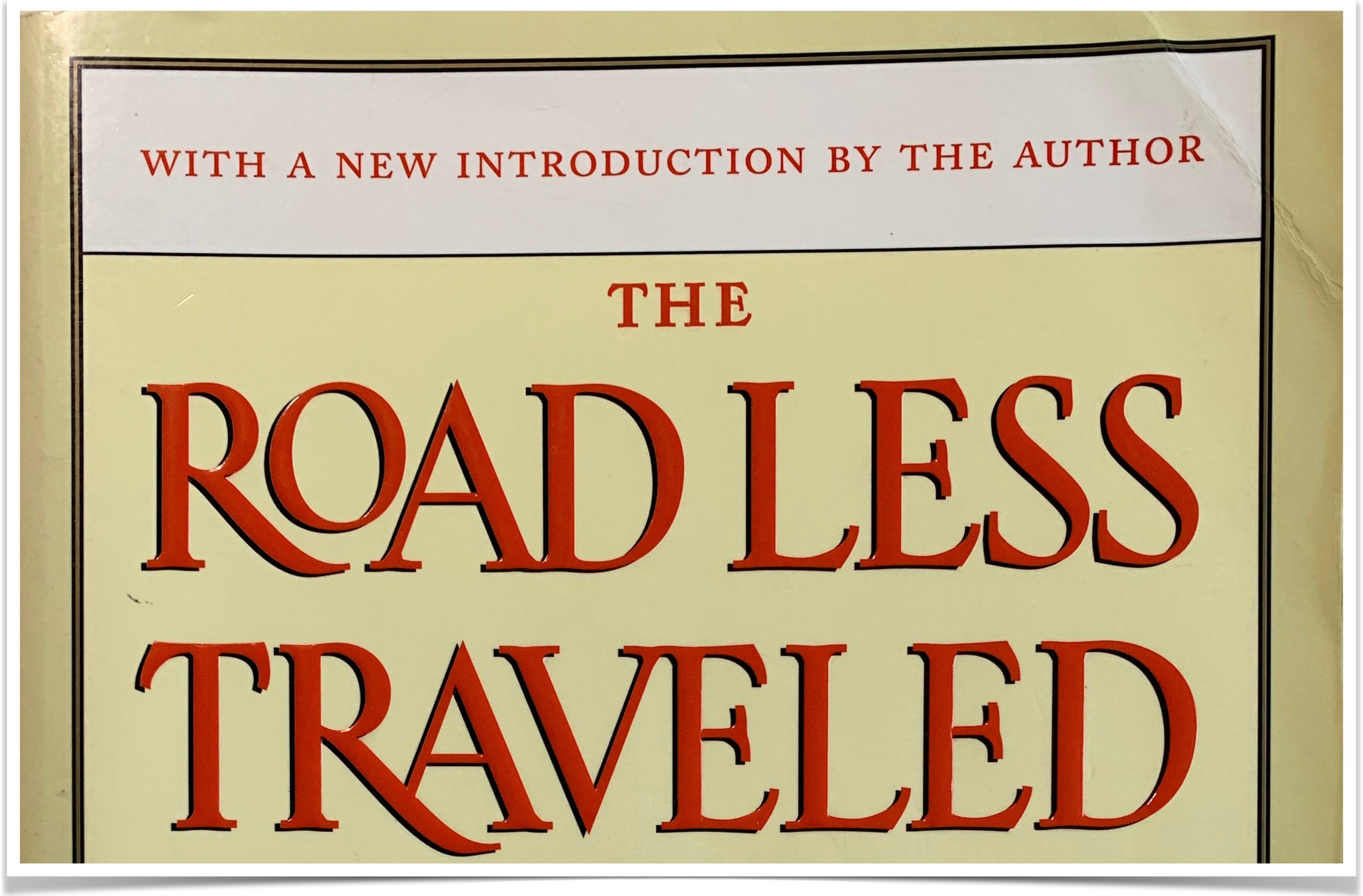
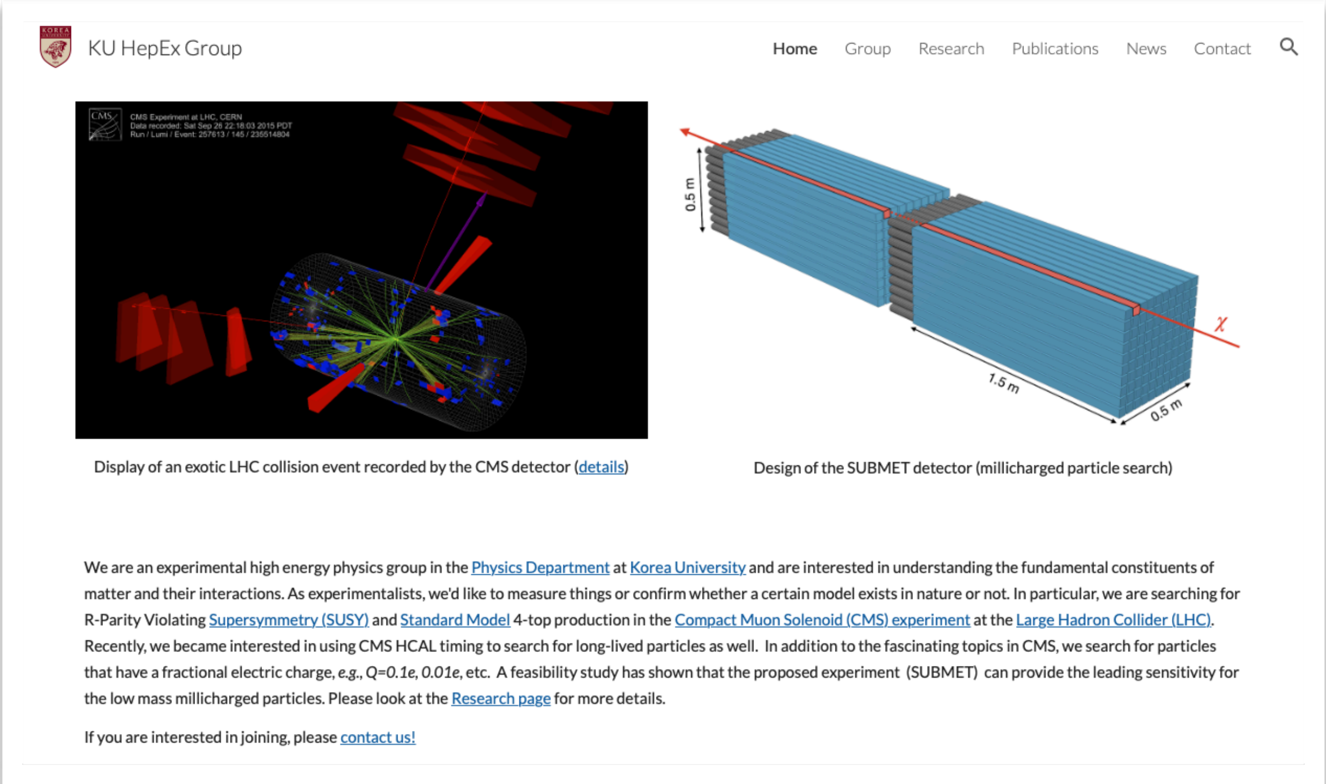


Where is new physics hidden?

Jae Hyeok Yoo (Korea University)
01/27/2022
XVIII Saga-Yonsei Joint Workshop

Introduction to myself

Myself 3 years ago …

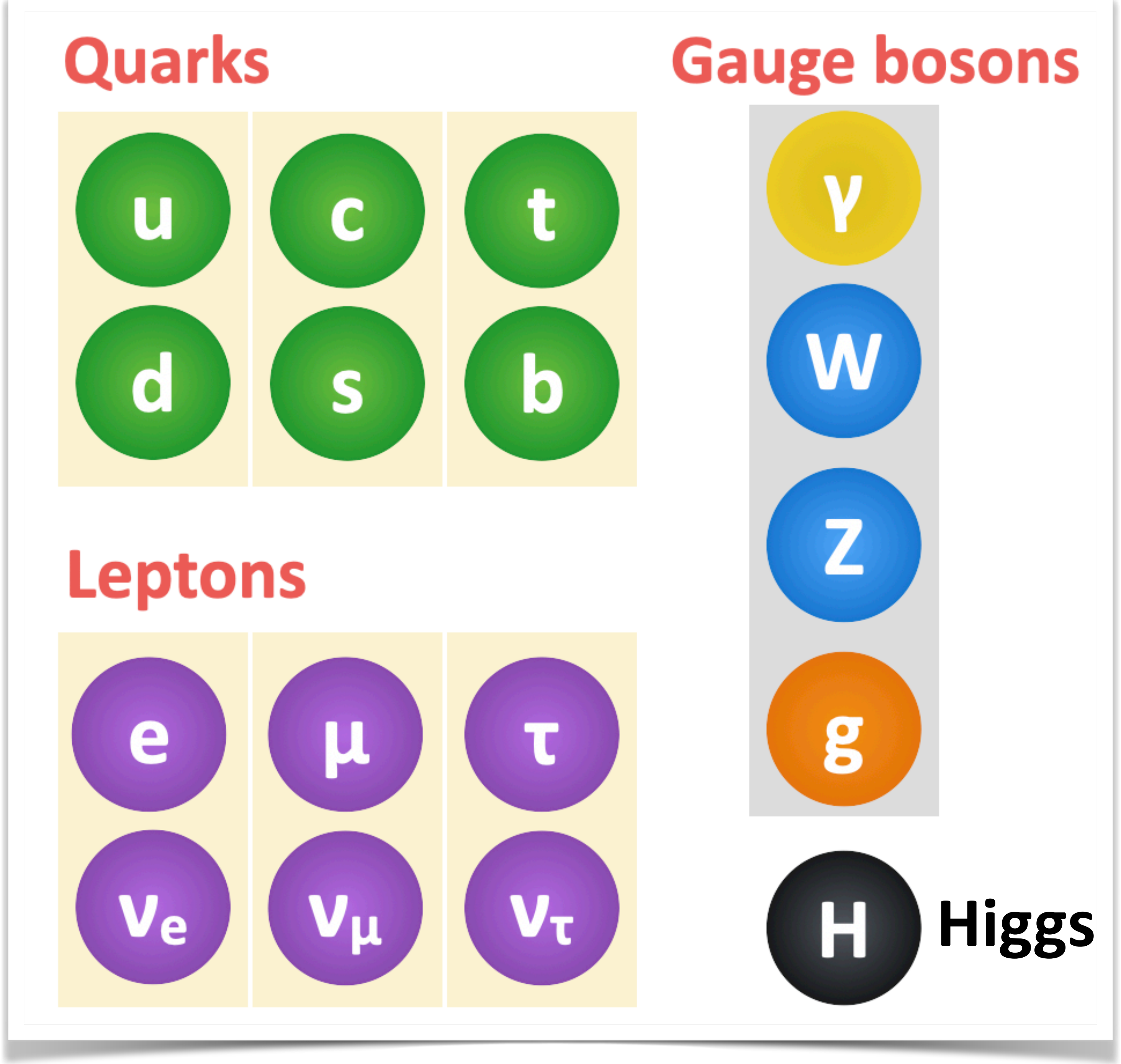


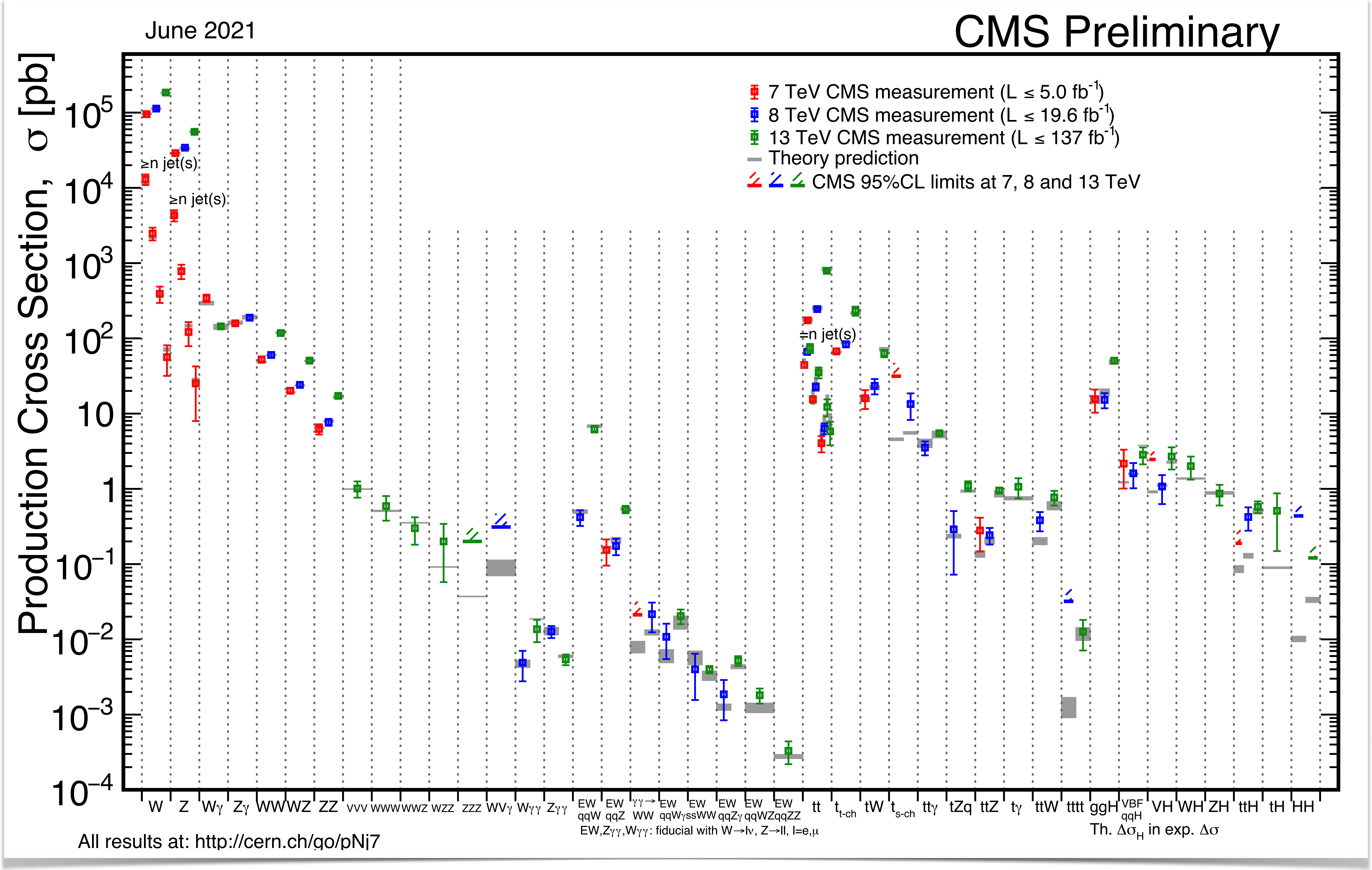
Group webpage. Click for more info!

- Name: Jae Hyeok Yoo
- Affiliation: Physics department, Korea University
- Research topics
  - **CMS**: RPV SUSY, SM 4top, LLP HCAL performance, MTD
  - **SUBMET**: Search for millicharged particle at J-PARC
- Due to my past experience in LHC since grad school, I am inevitably biased to LHC physics …

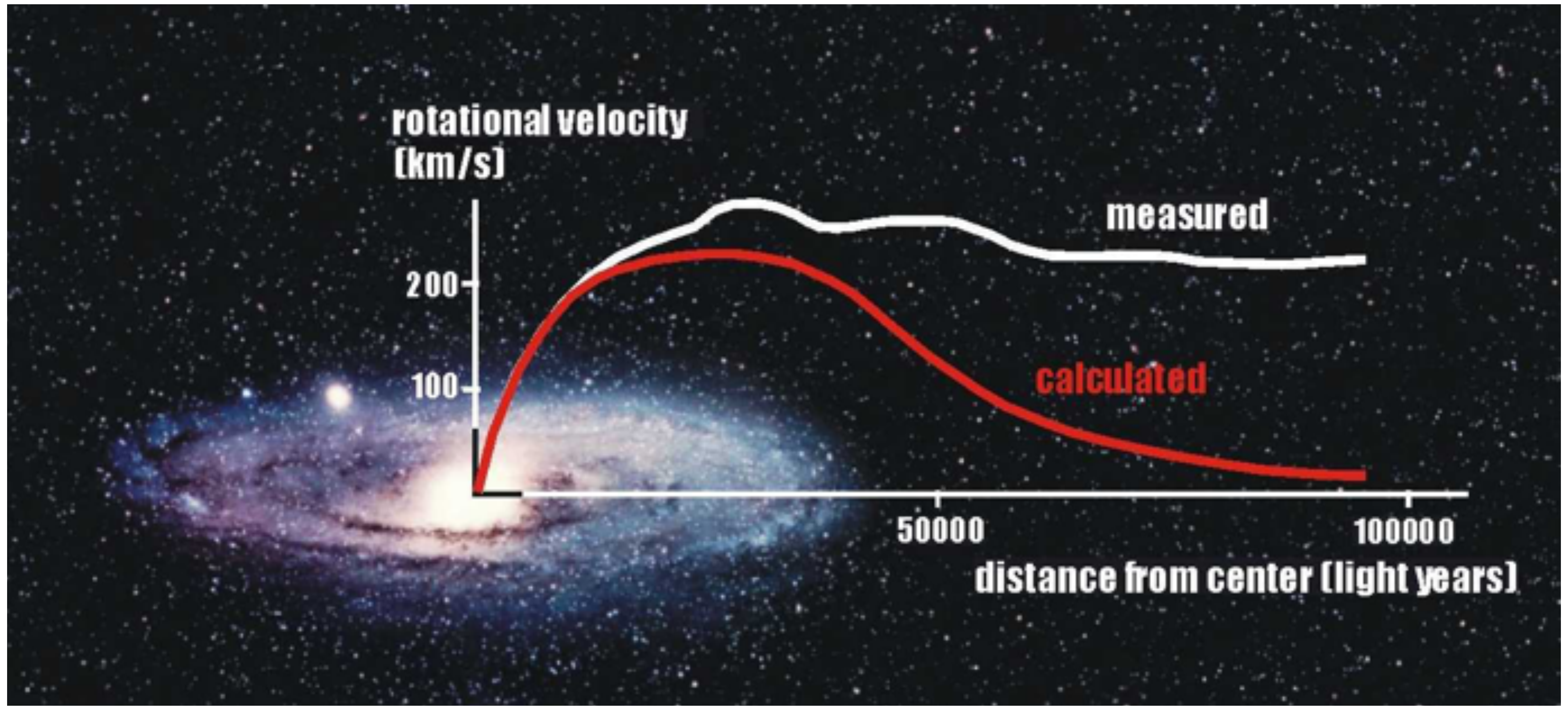
SM is extremely successful

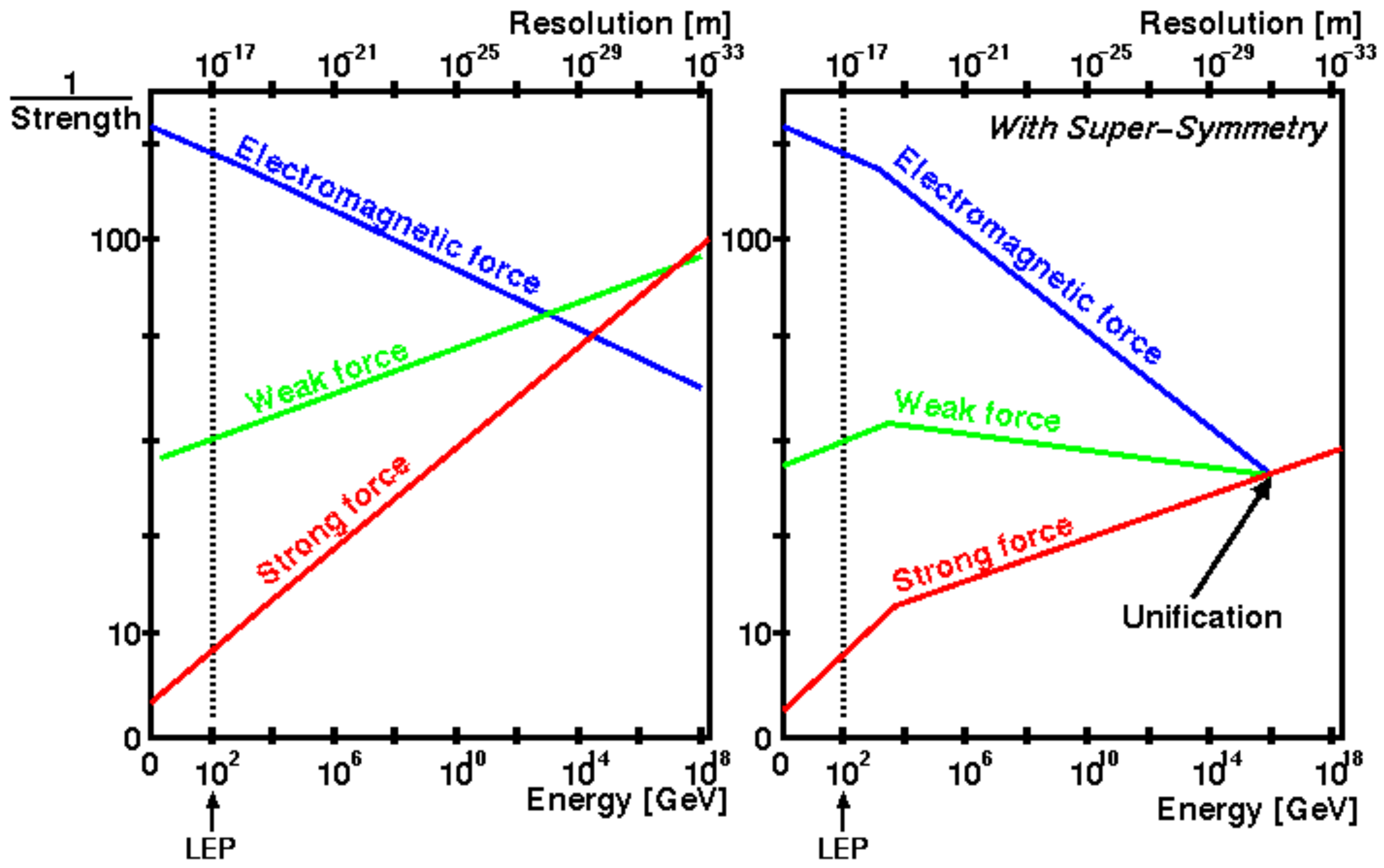
Standard Model (SM)





But, it is not complete





- Though SM is extremely successful, it has limitation to explain some experimental evidences for physics beyond it
  - e.g., cosmological evidence for existence of dark matter
- It also has some theoretical issues
  - Hierarchy problem, gauge unification, …
- There are ideas to explain these limitations
  - Supersymmetry has been one of the leading ideas

Why Supersymmetry (SUSY): hierarchy problem

- Hierarchy problem

$$m_h^2 = m_0^2 + \Delta m_h^2$$

physical mass: what we measure

bare mass: free parameter in the theory

loop correction: depends on cut off

Why Supersymmetry (SUSY): hierarchy problem

- Hierarchy problem

125^2 GeV^2

10^{34} GeV^2 at Λ=M$_{Planck}$

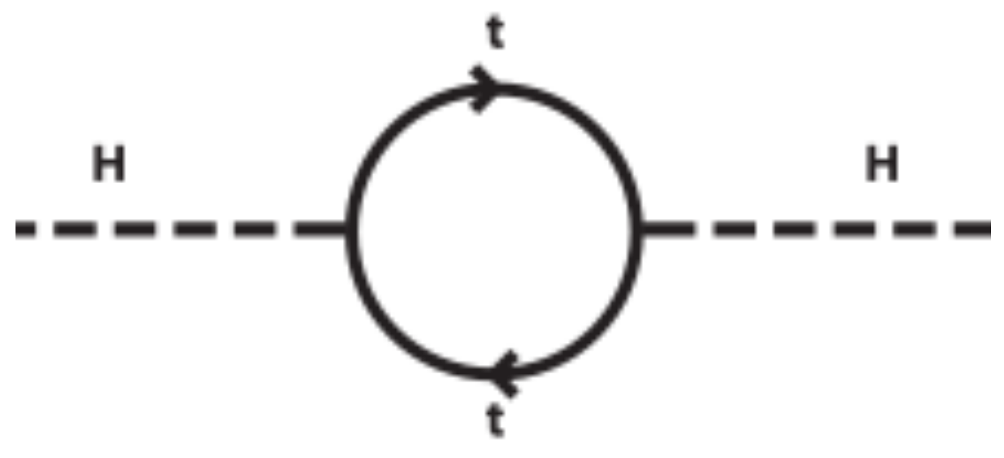
$$m_h^2 = m_0^2 + \Delta m_h^2$$

physical mass: what we measure

bare mass: free parameter in the theory

loop correction: depends on cut off

quadratic divergence



$$-\frac{3}{8\pi^2} g_f^2 \Lambda^2$$

Why Supersymmetry (SUSY): hierarchy problem

- Hierarchy problem

125^2 GeV2 $\qquad$ 10^{34} GeV2 at Λ=M$_{Planck}$

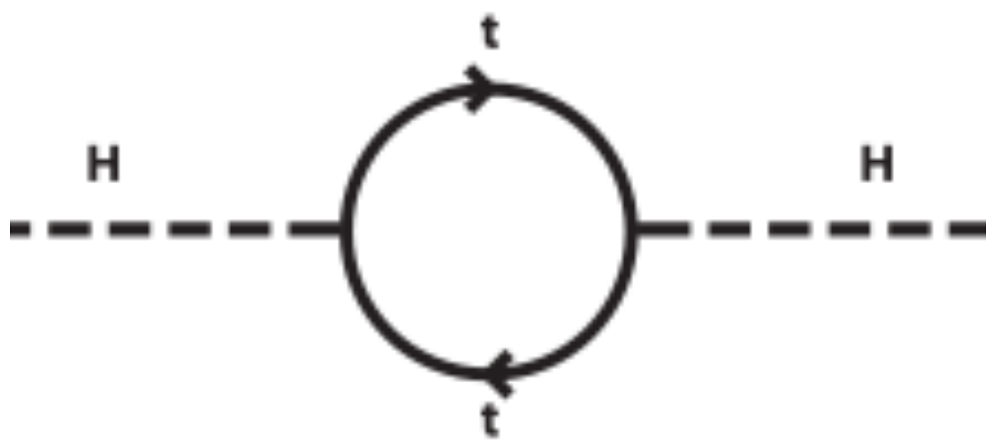
$$m_h^2 = m_0^2 + \Delta m_h^2$$

physical mass: what we measure

bare mass: free parameter in the theory

loop correction: depends on cut off

quadratic divergence



$$-\frac{3}{8\pi^2} g_f^2 \Lambda^2$$

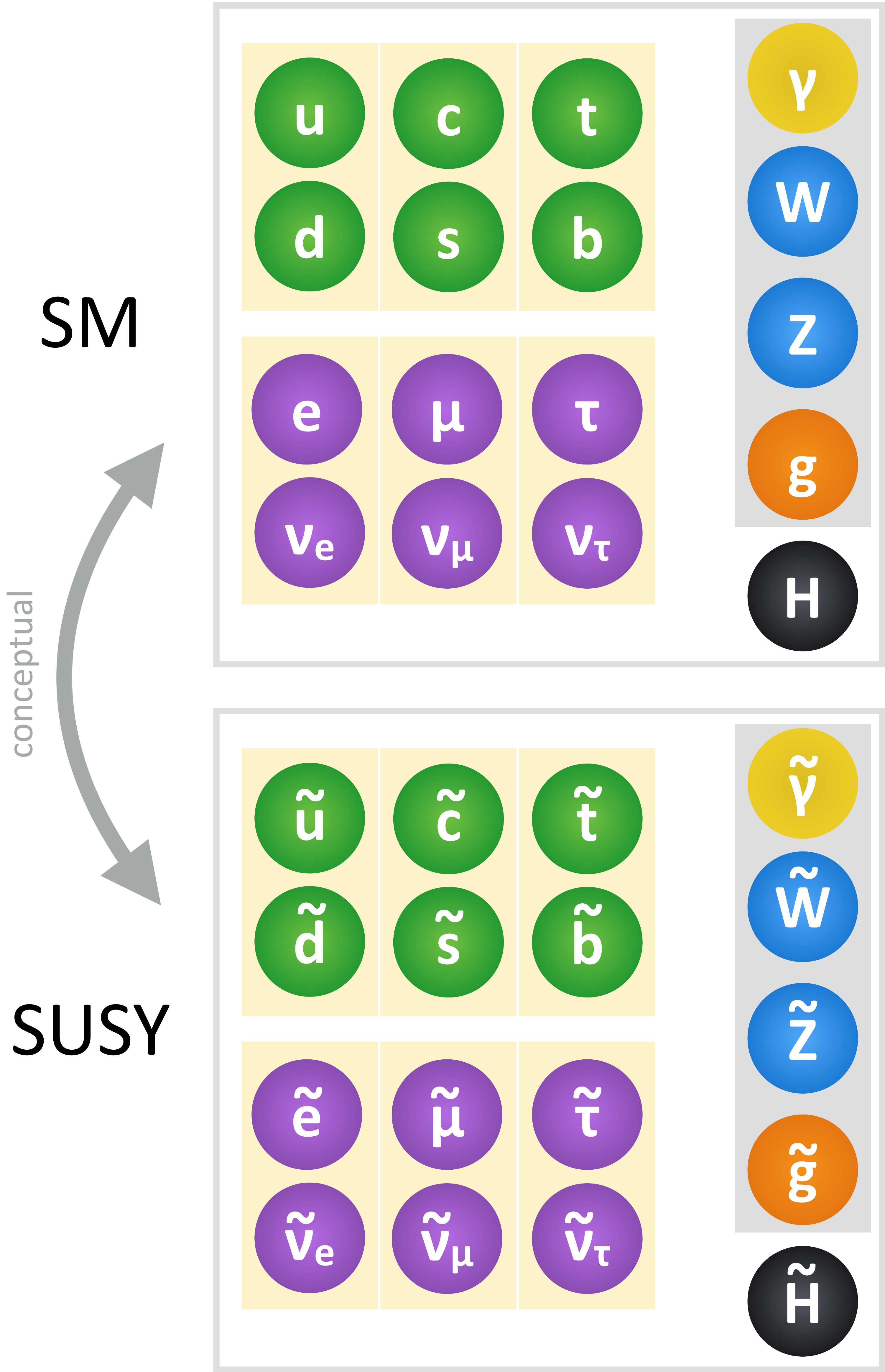
Hierarchy problem

why is Higgs mass so much less than the scale of gravity?

Fine-tuning

m_0^2 should be fine-tuned to give $m_h^2 = 125^2$ GeV2

Search for Supersymmetry (SUSY)



- SUSY solves this problem by introducing partners of each SM particle with spin different by 1/2
  - "fermion => boson" and "boson => fermion" partners
- Fermions and bosons have opposite signs in quantum correction calculation

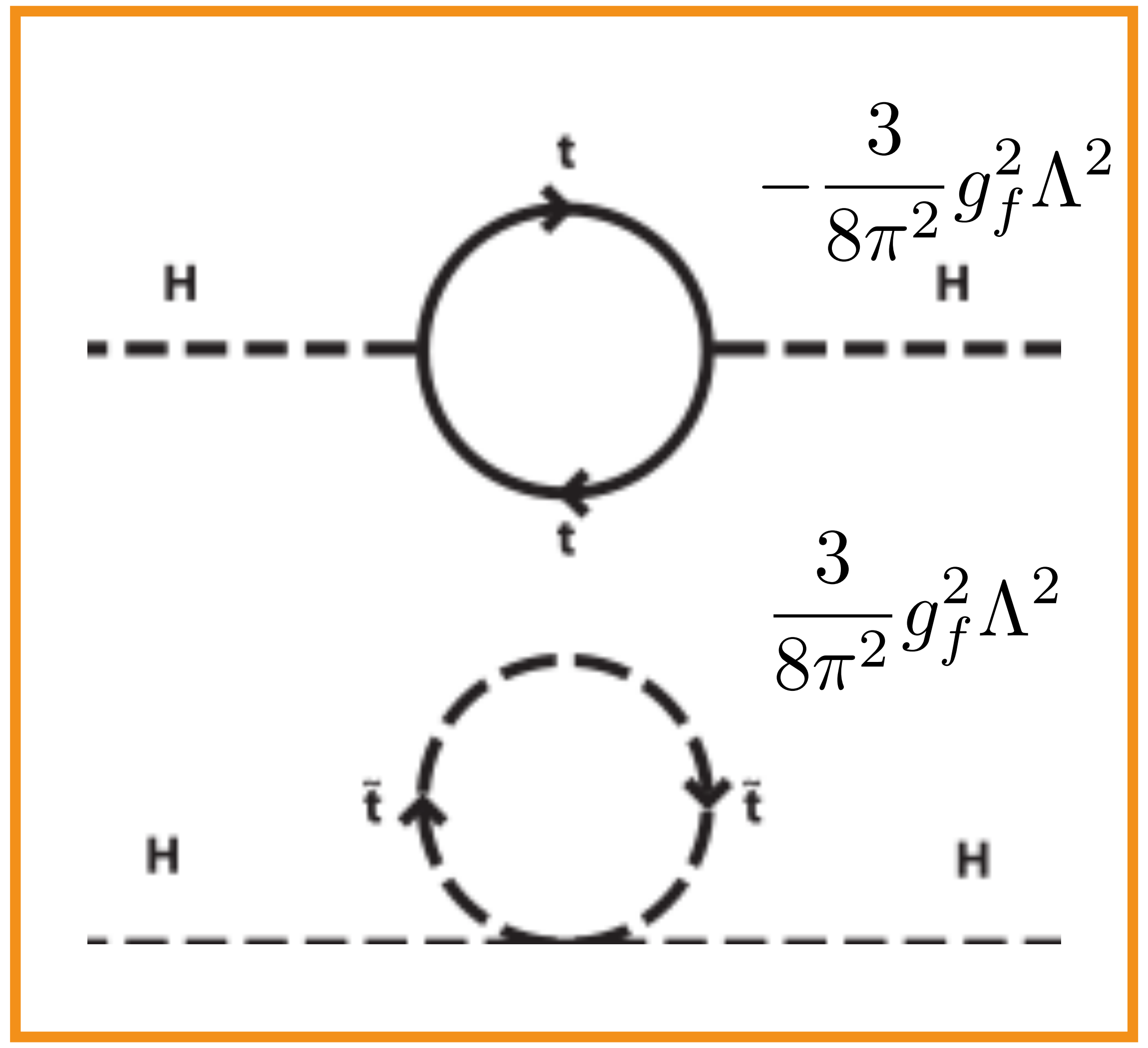
$$m_h^2 = m_0^2 + \Delta m_h^2$$

logarithmic divergence $-\frac{3}{8\pi^2} g_f^2 (m_{\tilde{t}}^2 - m_t^2) \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$

Naturalness argument

$m_{\tilde{g}} < \sim 2$ TeV

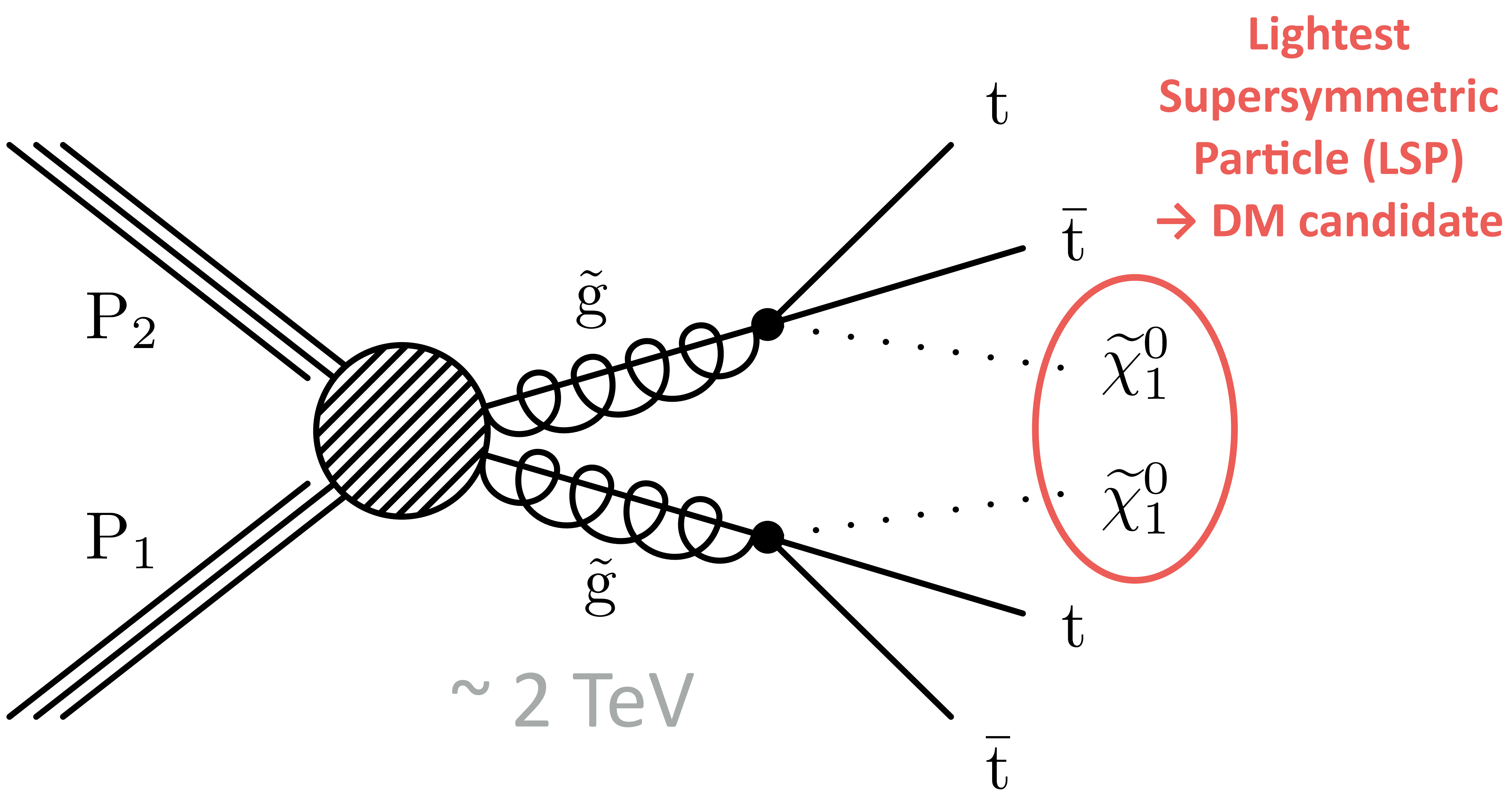
$m_{\tilde{t}} < \sim 1$ TeV



Quadratic divergence term gone!

R-Parity Conservation (RPC)

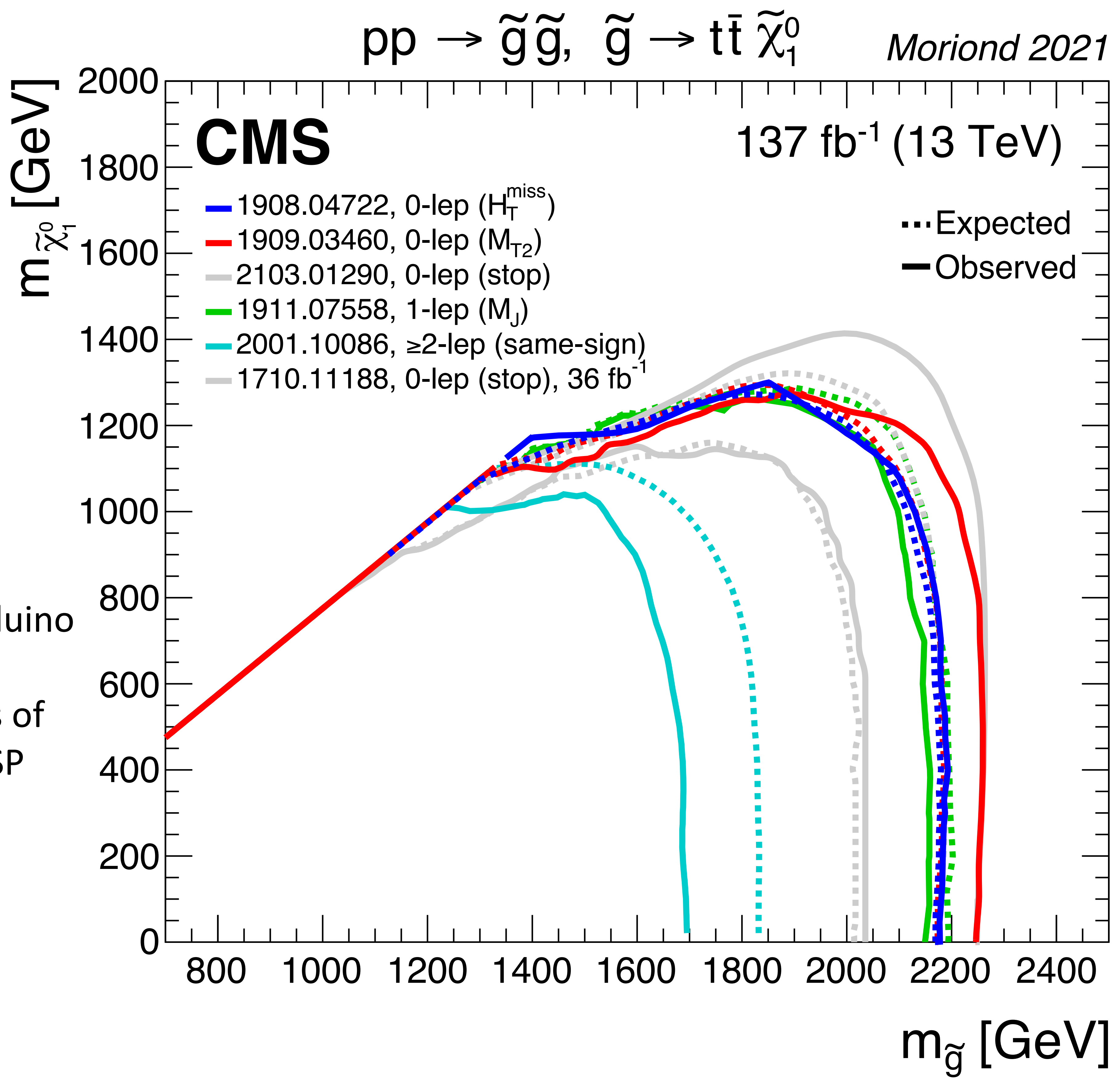
An example of RPC model

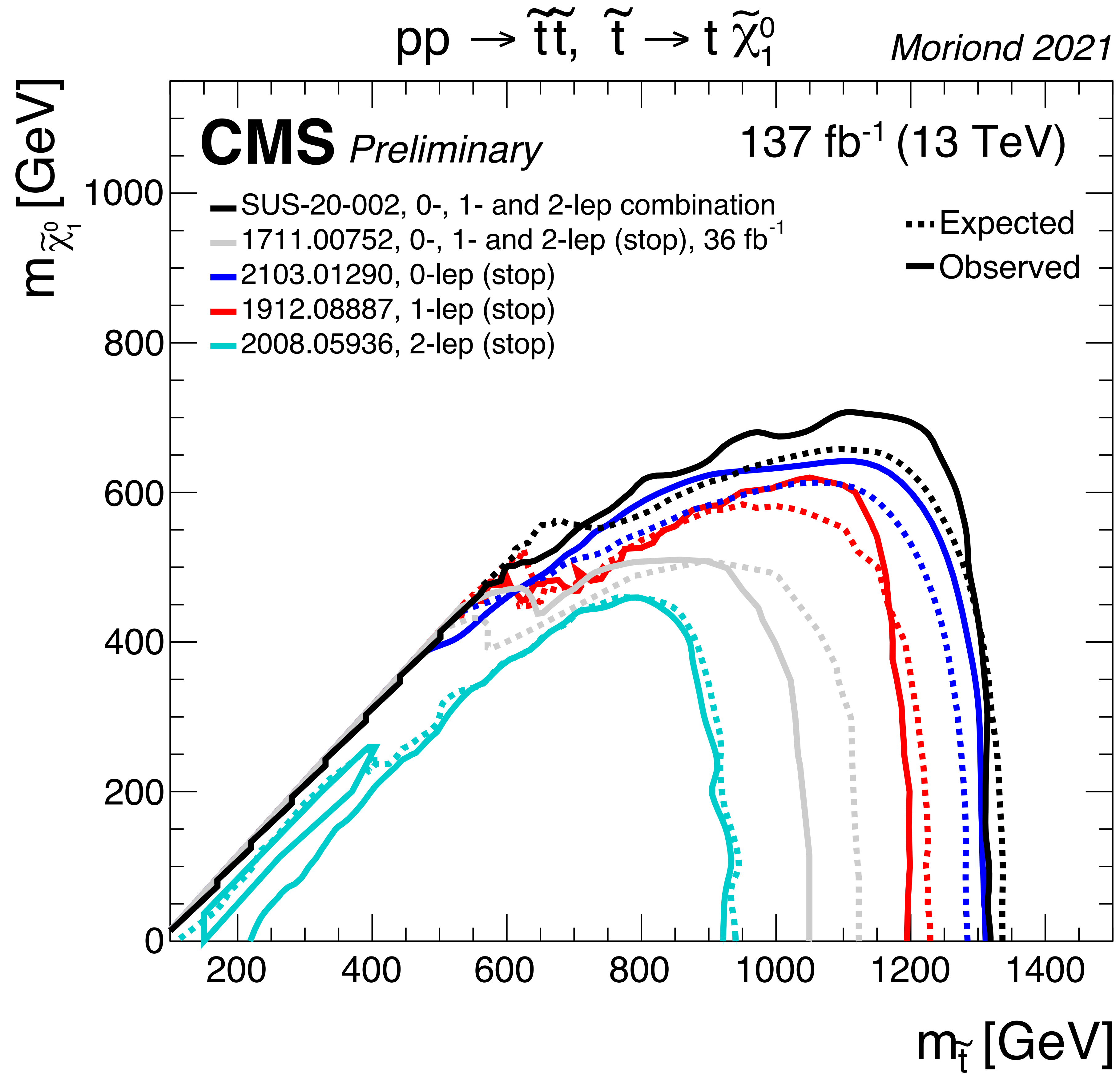


- **R-parity = $(-1)^{3B+L+2s}$**
  - Conservation of B and L
  - SM particles: +1, SUSY particles: -1
  - If conserved, SUSY particles produced in pairs at LHC
  - Lightest SUSY Particle (LSP) is stable → if Q=0, it is a dark matter candidate
- Because R-Parity conservation provides dark matter candidate and is favored by long proton lifetime, it is a preferred assumption for SUSY searches
  - Most SUSY searches have targeted RPC models

Recent SUSY Searches

Mass limits for a simplified model of gluino pair production with gluino decays to pairs of top quarks and the LSP

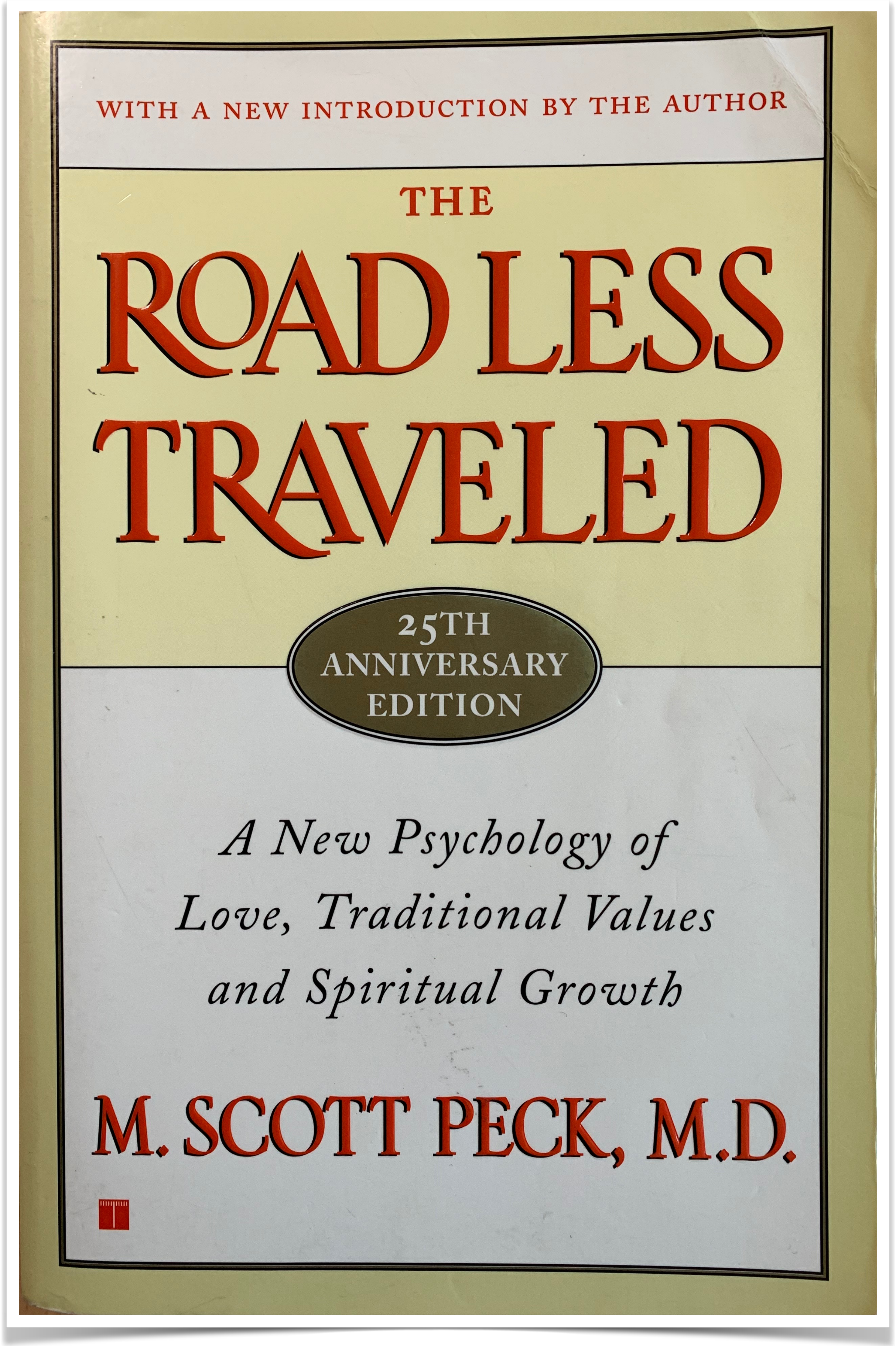




Mass limits for a simplified model of top squark pair production with squark decays to a on- or off-shell top quark and the LSP, leading to final states with two bottom quarks, two W bosons, and two LSPs

- Recent searches at LHC set stringent limits on R-parity conserving (RPC) models: excluded $m_{\tilde{g}} < 2$ GeV, $m_{\tilde{t}} < 1$ GeV region (tension in ability to explain hierarchy problem with little fine tuning)

Where to look?

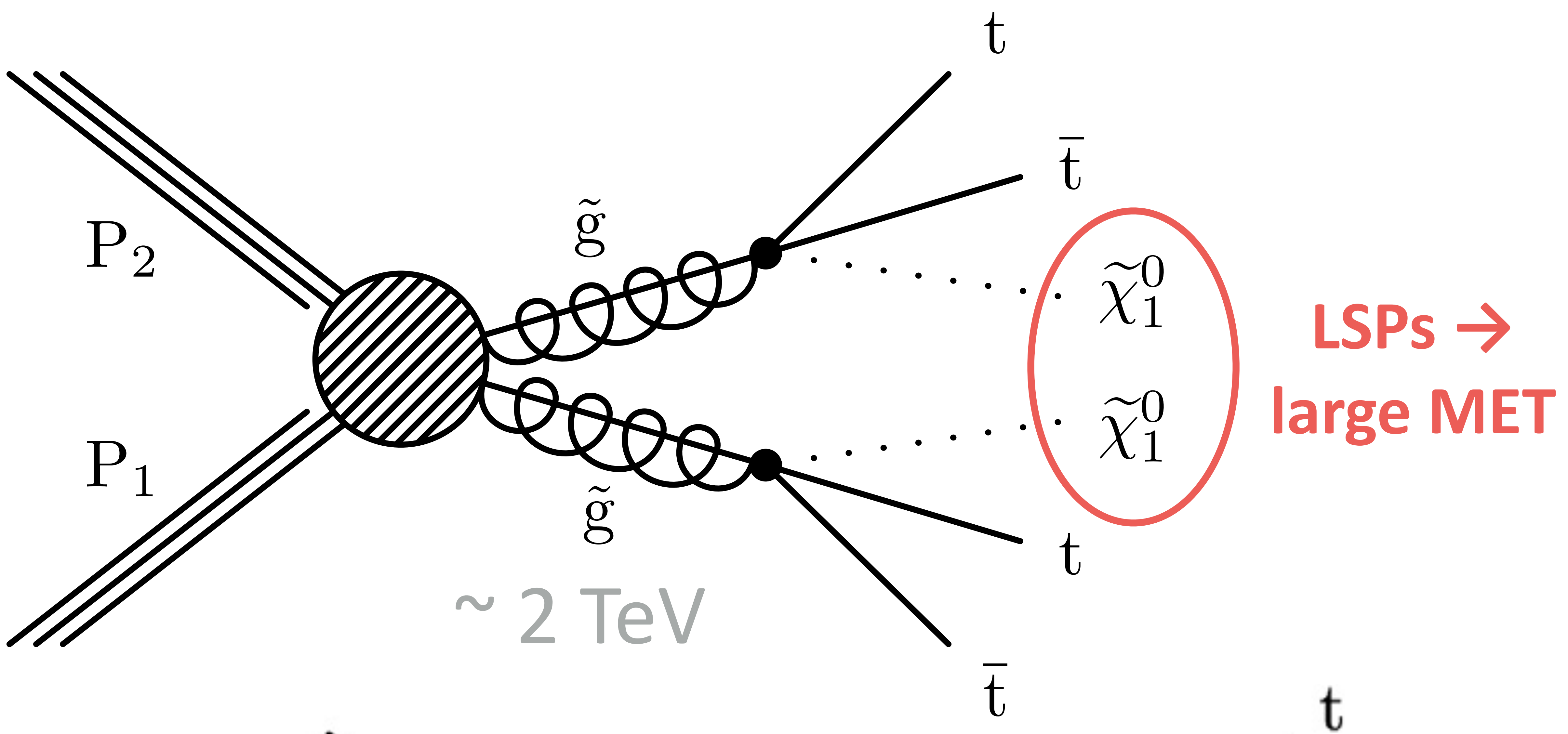


- **No sign of new physics does NOT mean that new physics does not exist**
  - It just means that it does not exist where we thought it would be
- Now is the time to travel the roads less traveled
- Using the capability of the CMS detector
  - Probe new signatures, e.g., long-lived particles
  - Give up some assumptions, e.g., **R-Parity Violating (RPV) SUSY**
- **Build a new (small) detector** to search for signatures CMS is not designed to sensitive to

Why R-Parity Violating (RPV) SUSY?

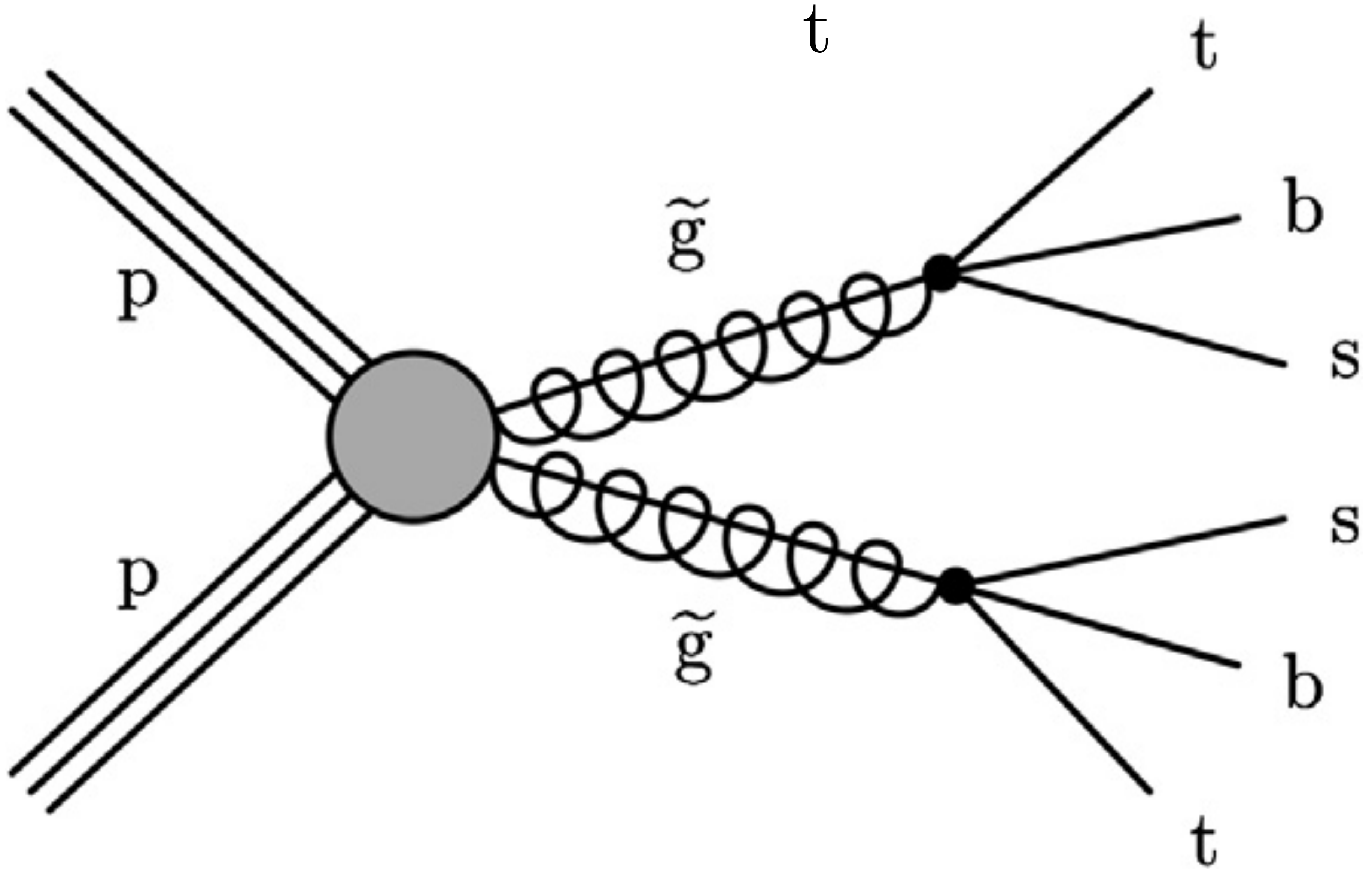
RPC

model



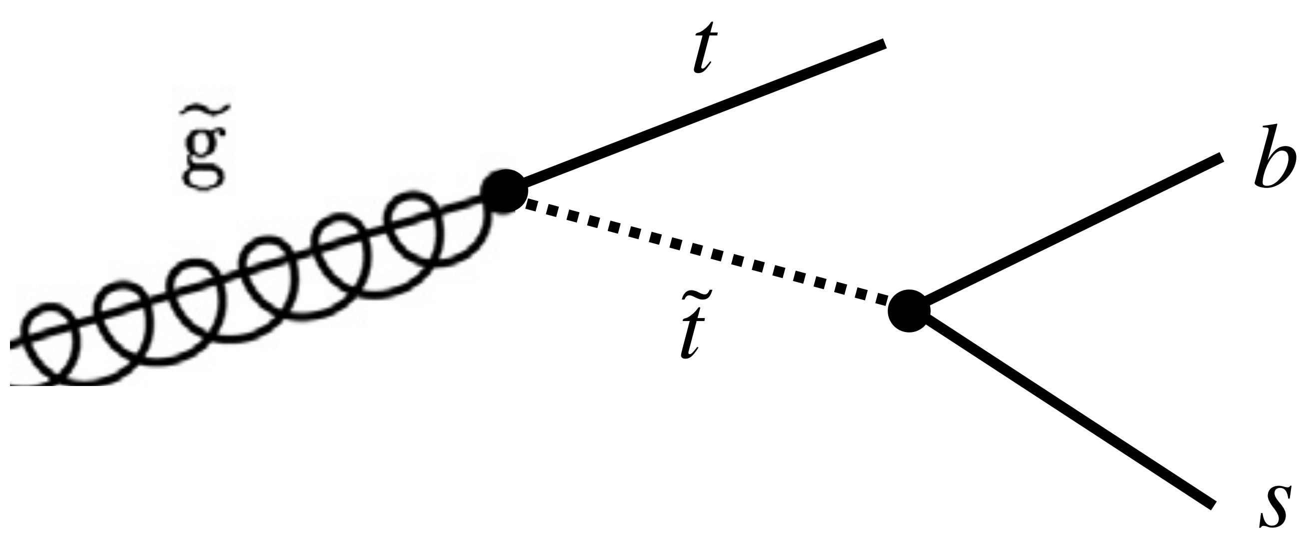
RPV

model

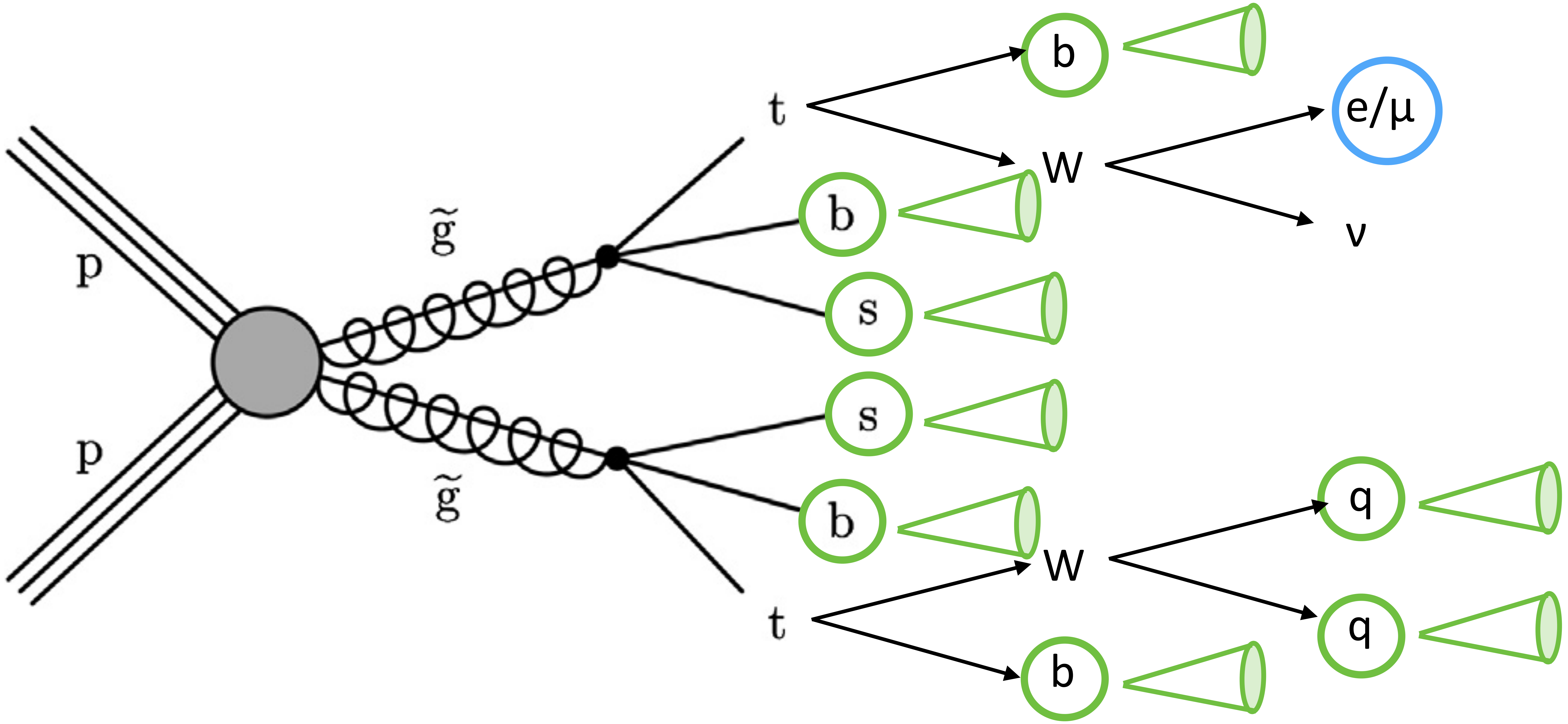


- **RPC** searches require **significant amount of Missing Transverse Energy (MET)** due to undetected LSPs
- In **RPV** scenarios LSP can decay to SM particles → **removes large MET signature** → **RPC searches kill such signal**
- This disfavors LSP as a DM candidate, but can weaken constraints from RPC searches

1L RPV SUSY search in CMS

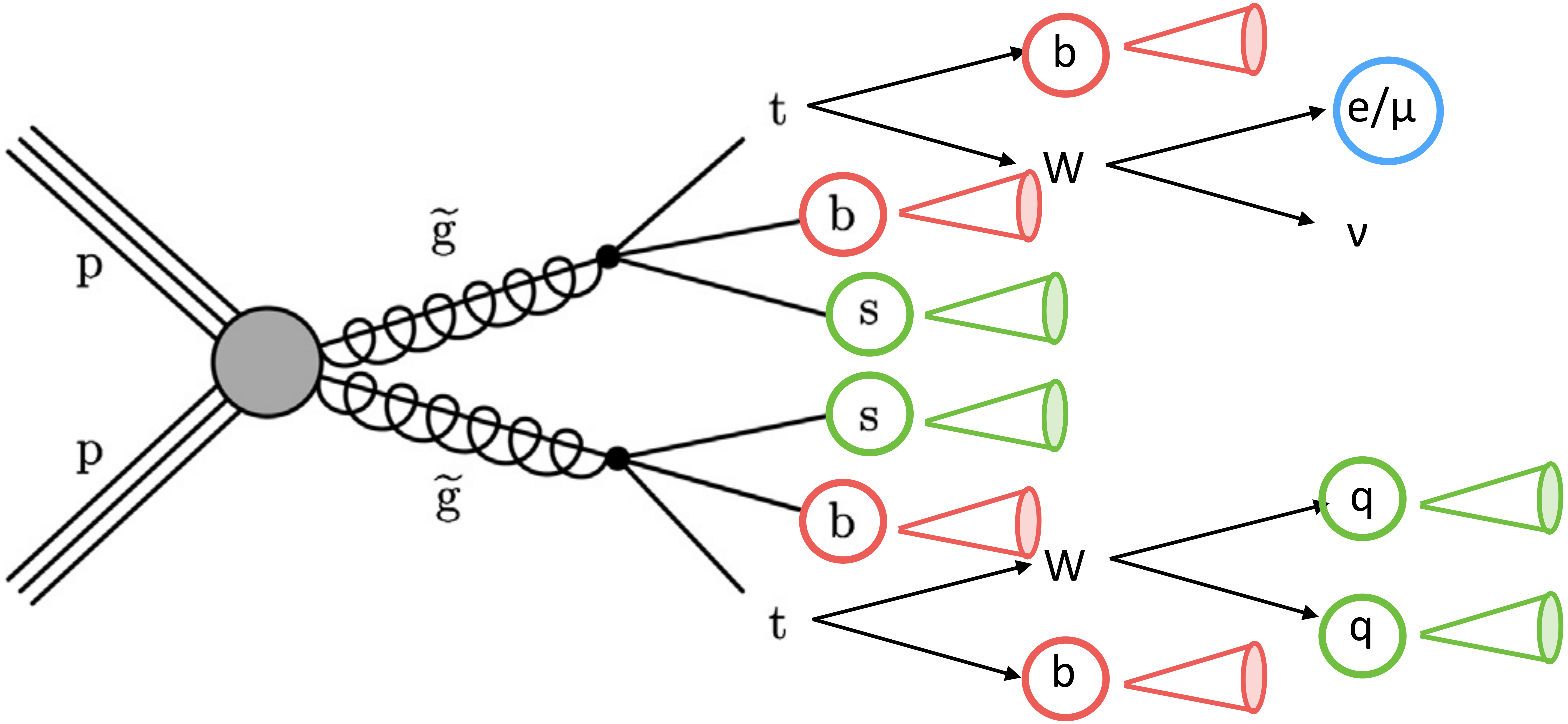


- Target gluino pair production where gluino decays to tbs (via B-number violating interaction)
  - Motivated by minimum flavor violating SUSY which makes 3rd generation couplings large
- 1-lepton final state with large jet



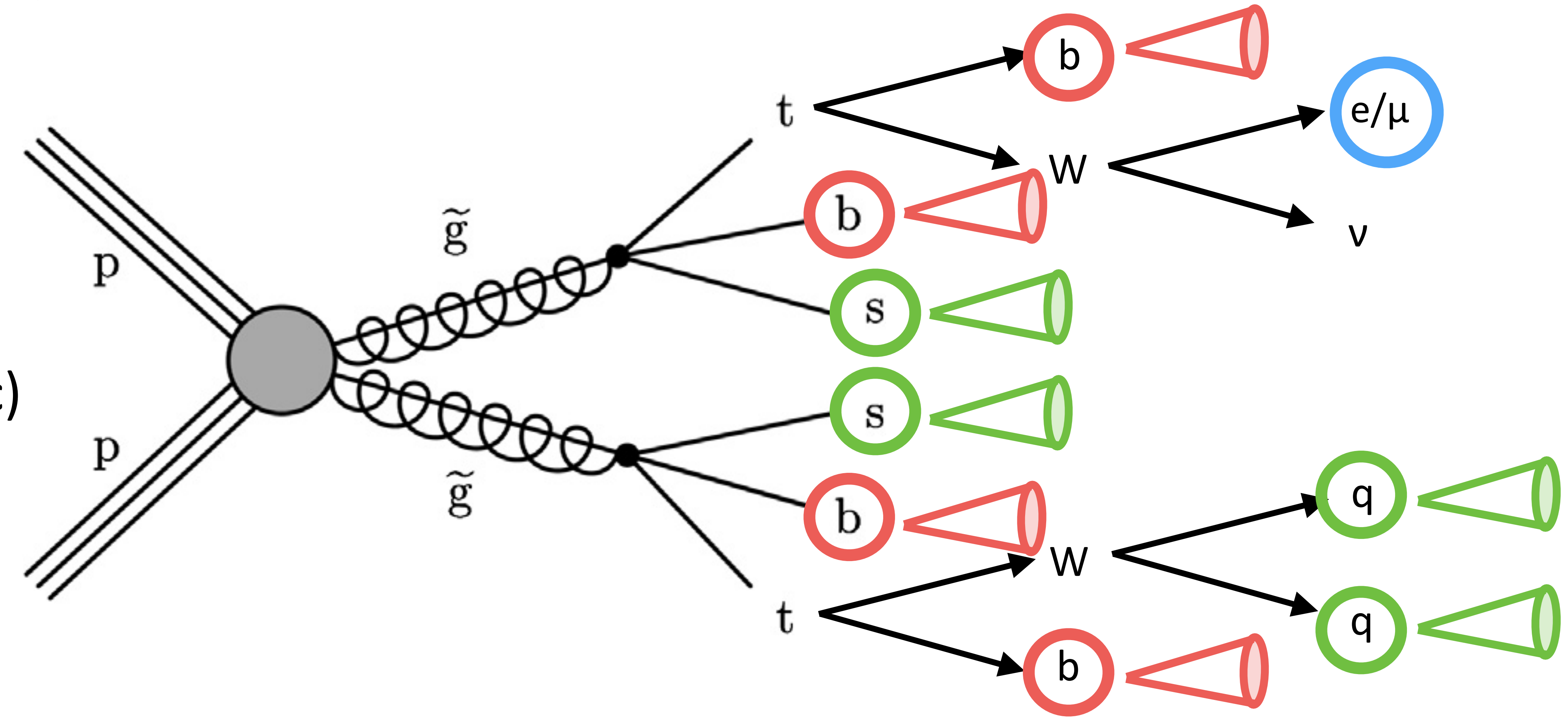
1L RPV SUSY search in CMS

- Target gluino pair production where gluino decays to tbs (via B-number violating interaction)
  - Motivated by minimum flavor violating SUSY which makes 3rd generation couplings large
- 1-lepton final state with large jet and b jet multiplicities and **no MET requirement**



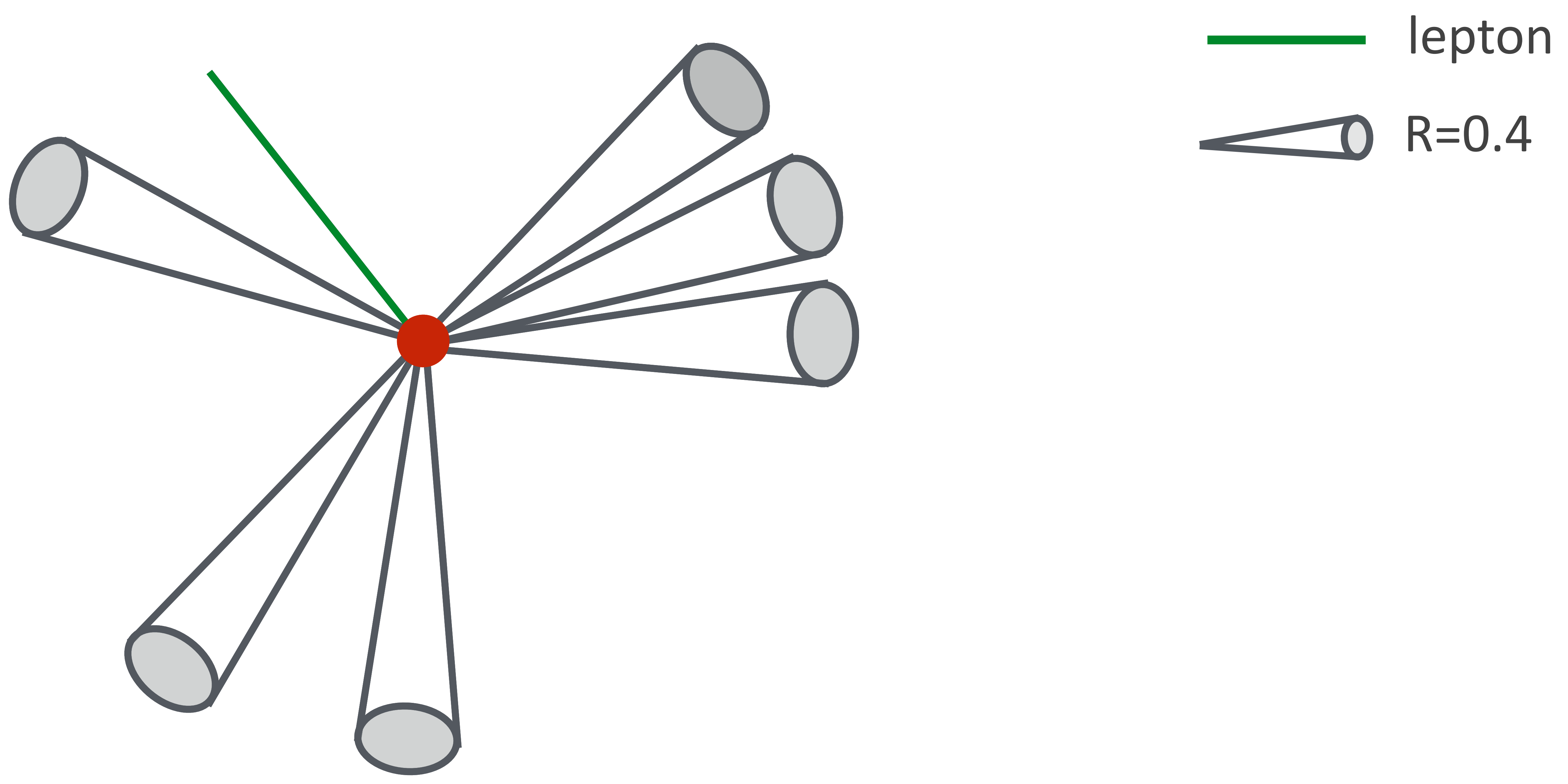
1L RPV SUSY search in CMS

- Target gluino pair production where gluino decays to tbs (via B-number violating interaction)
  - Motivated by minimum flavor violating SUSY which makes 3rd generation couplings large
- **1-lepton** final state with **large jet** and **b jet multiplicities** and **no MET requirement**
  - Generic search sensitive to such high-mass signatures
- Backgrounds
  - $t\bar{t}$ (dominant), QCD, W+jets, and other (single top, Drell-Yan, di-boson, etc)



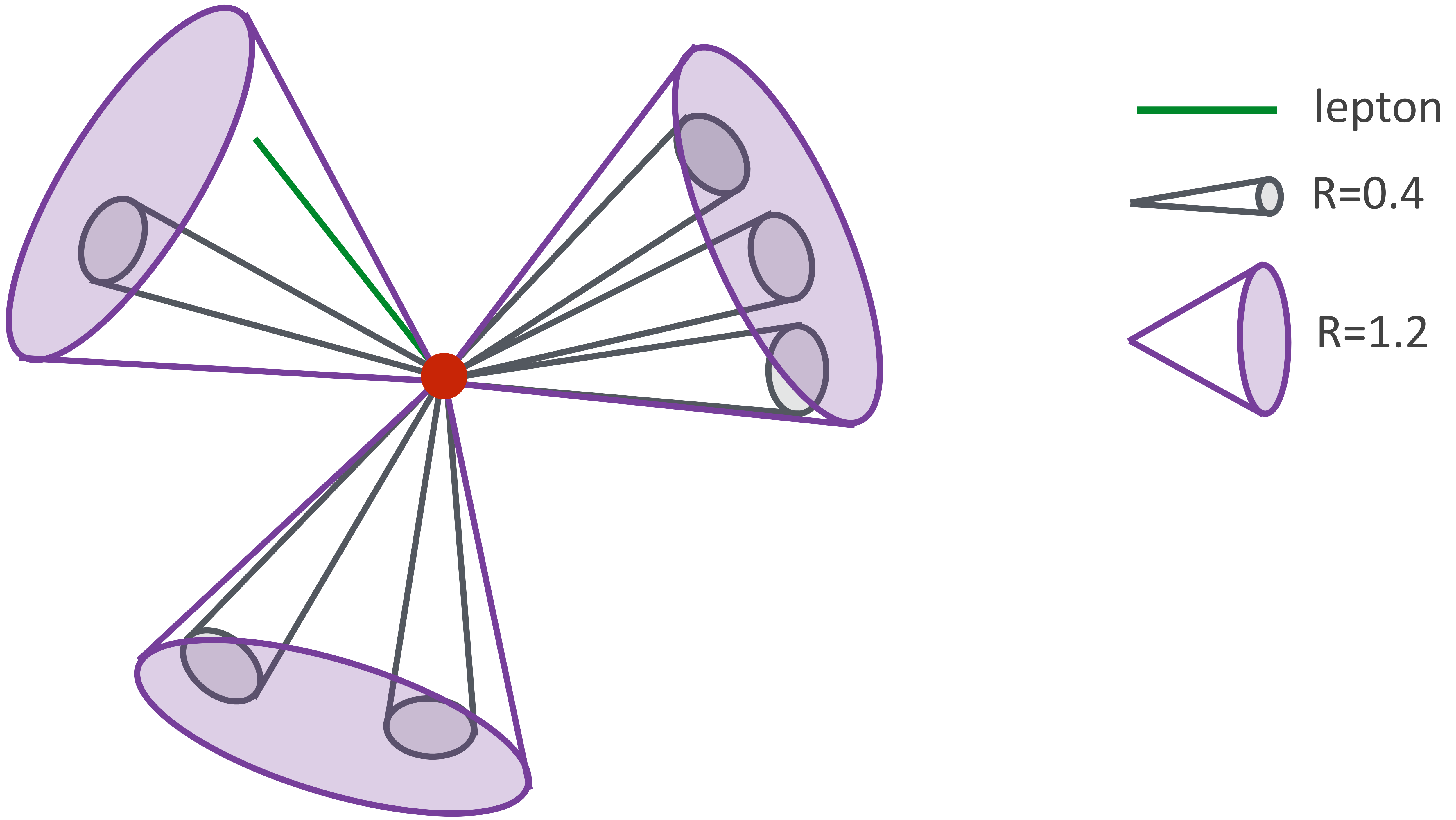
Novel variable: M_J

- **M_J**: scalar sum of masses of large-R (R=1.2) jets
- To form a large-R jet, regular (R=0.4) jets and leptons are clustered together



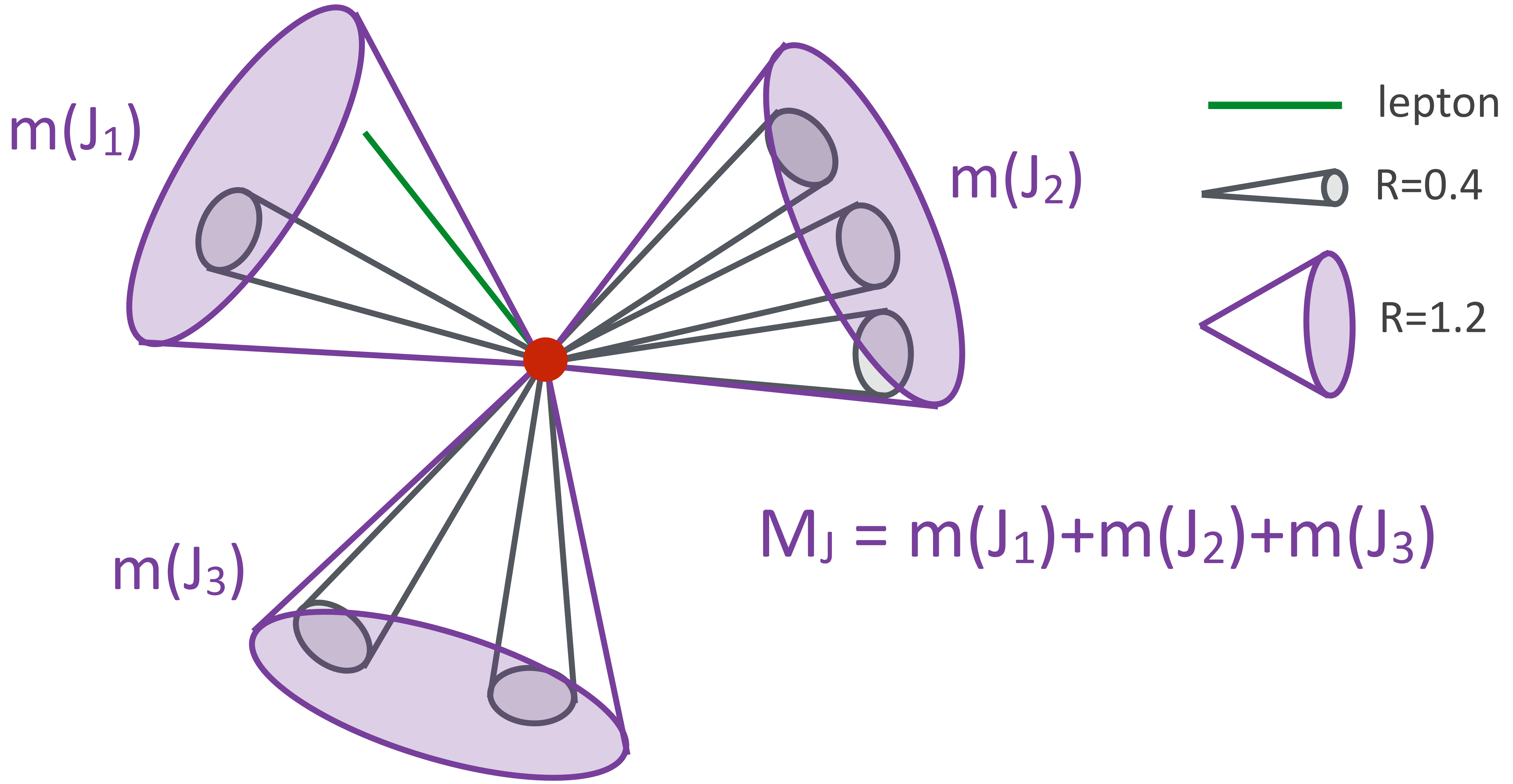
Novel variable: M_J

- **M_J**: scalar sum of masses of large-R (R=1.2) jets
- To form a large-R jet, regular (R=0.4) jets and leptons are clustered together



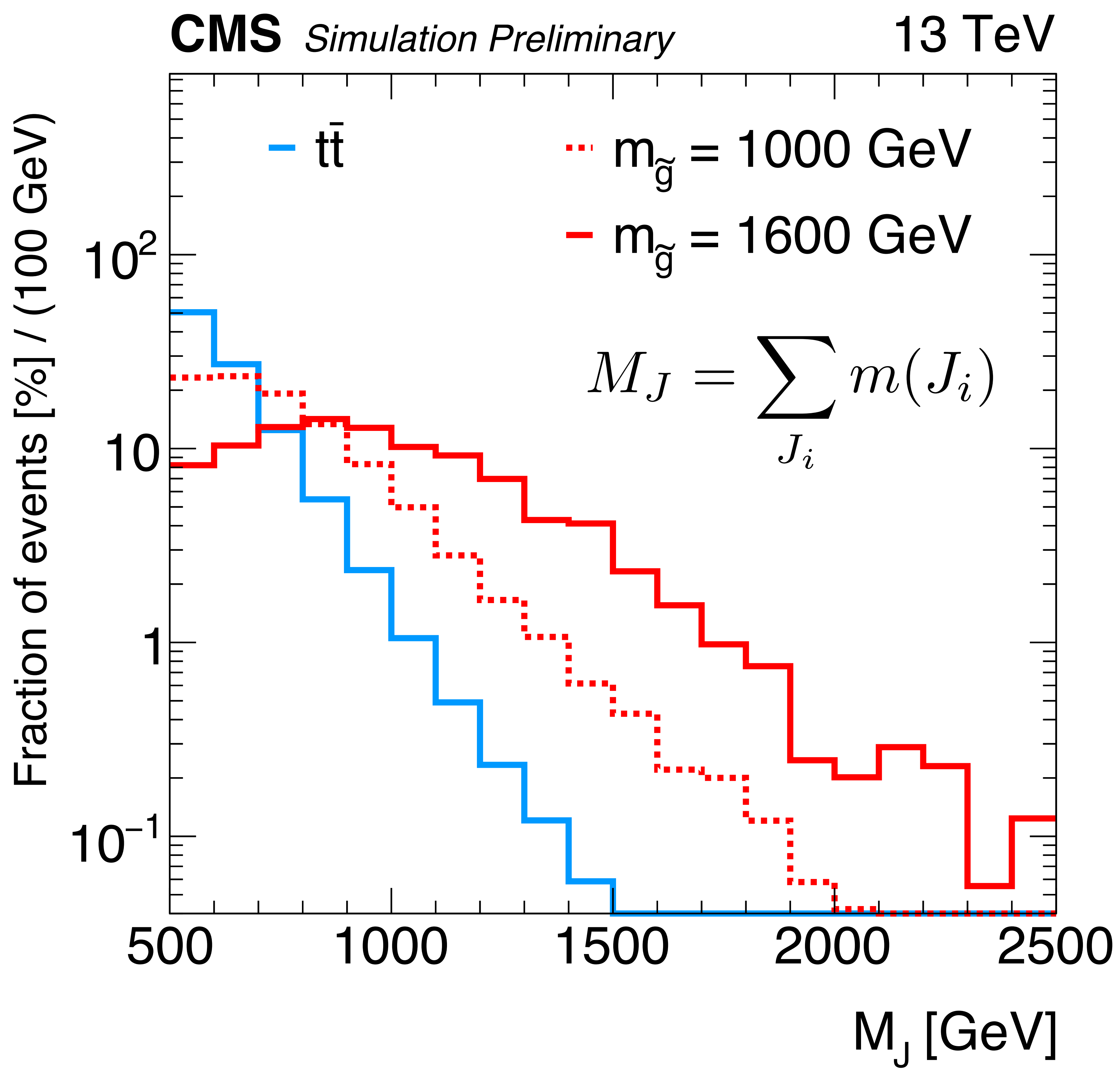
Novel variable: M_J

- **M_J**: scalar sum of masses of large-R (R=1.2) jets
- To form a large-R jet, regular (R=0.4) jets and leptons are clustered together



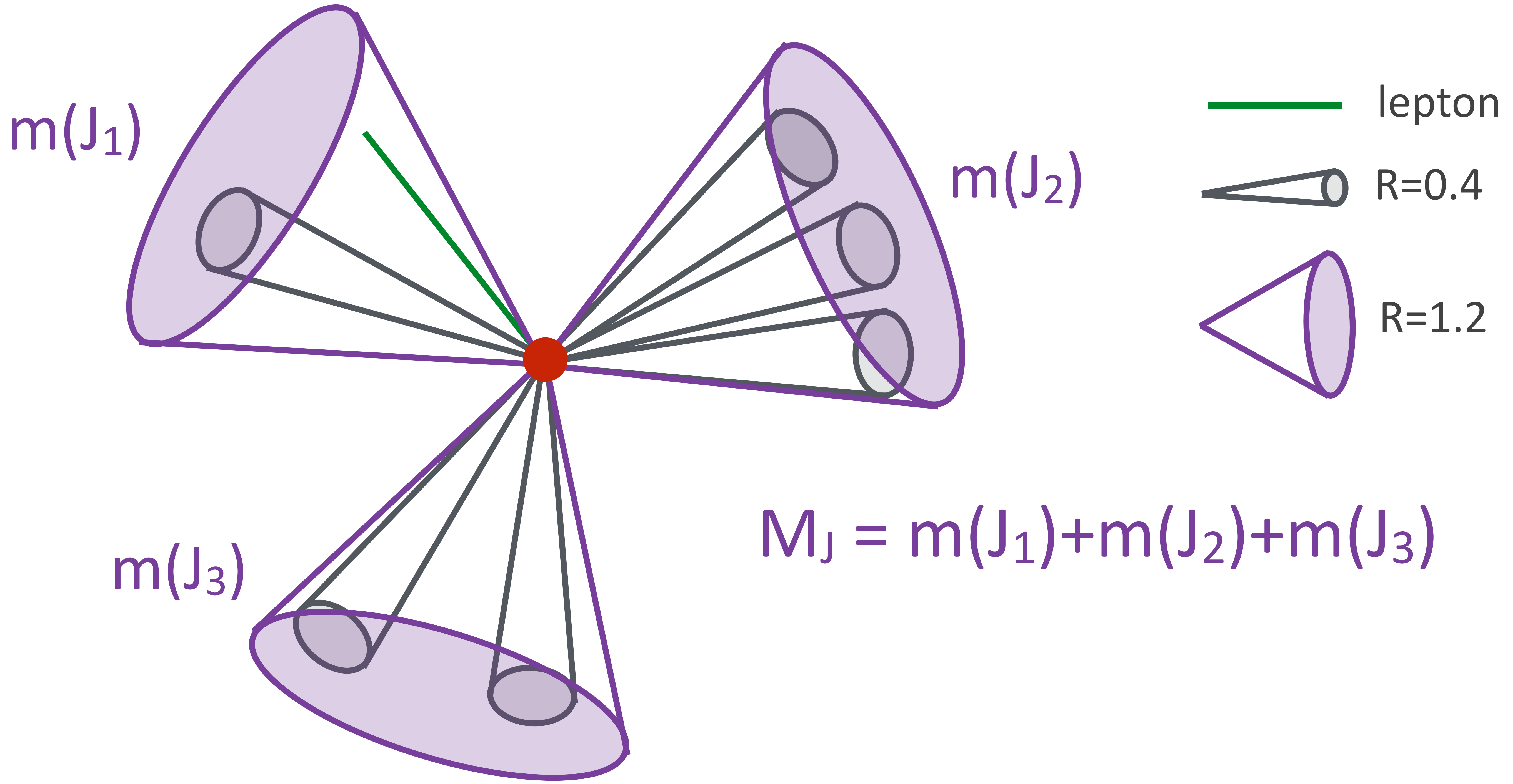
$M_J = m(J_1)+m(J_2)+m(J_3)$

Novel variable: M_J



Use M_J to suppress background

- **M_J**: scalar sum of masses of large-R (R=1.2) jets
- To form a large-R jet, regular (R=0.4) jets and leptons are clustered together



Analysis strategy

Use three variables to distinguish signal from background: $\mathbf{N_b}$, $\mathbf{N_{jet}}$ and $\mathbf{M_J}$

Analysis strategy

Use three variables to distinguish signal from background: $\mathbf{N_b}$, $\mathbf{N_{jet}}$ and $\mathbf{M_J}$

Make bins of (N_b, N_{jet}) and use M_J distribution in each bin

* Baseline selection: N_{lep}=1, H_T>1200 GeV, M_J>500 GeV, N_{jet}≥4 and N_b≥0

Analysis regions

N_b	N_{jet}		
	4-5 (low)	6-7 (med)	≥8 (high)
0			
1			
2			
3			
≥4			

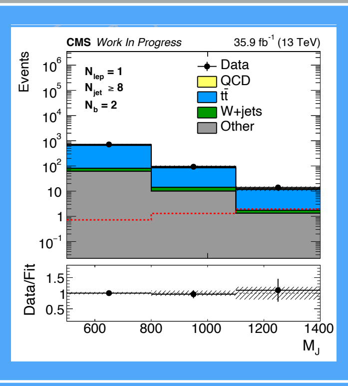
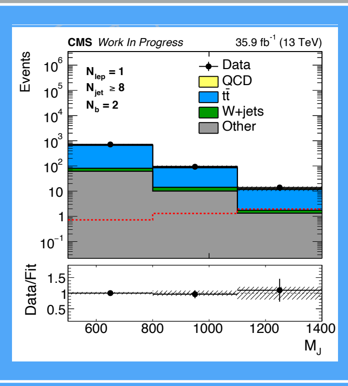
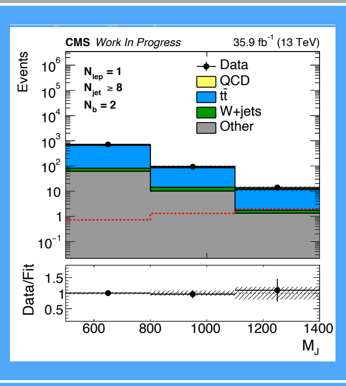
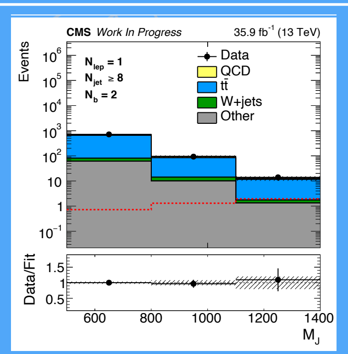
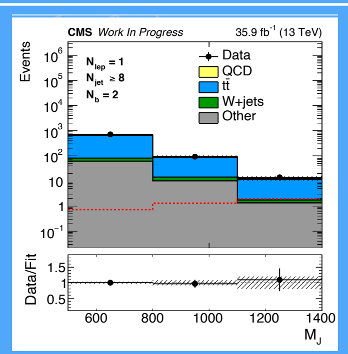
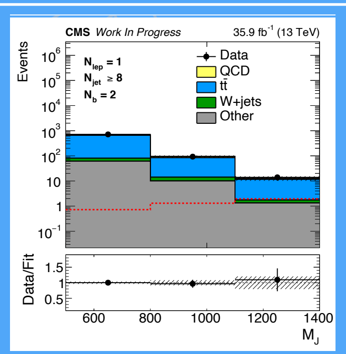
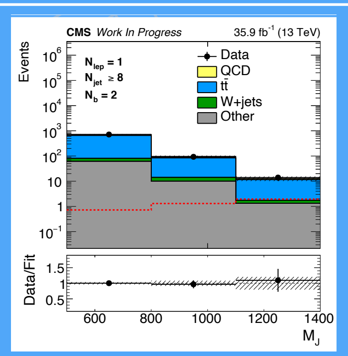
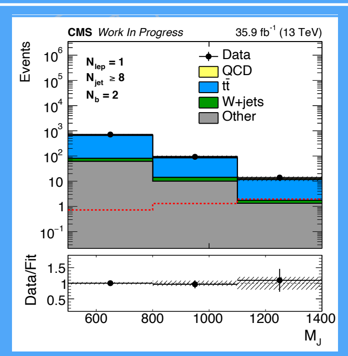
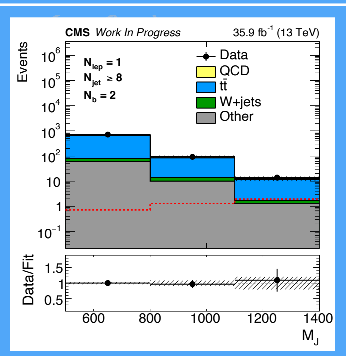
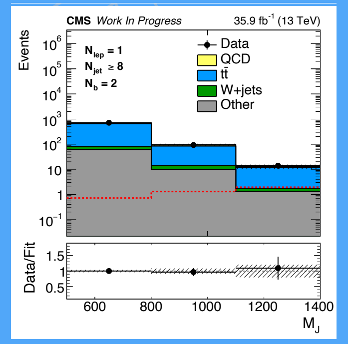
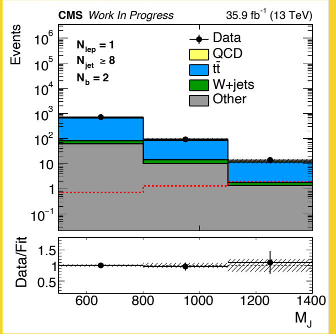
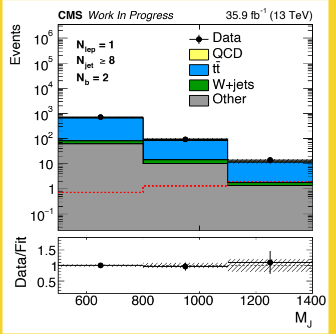
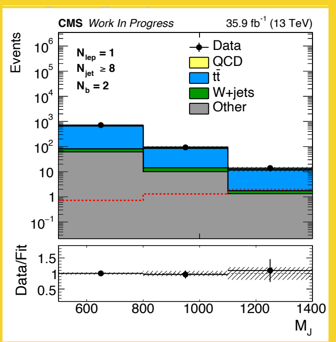
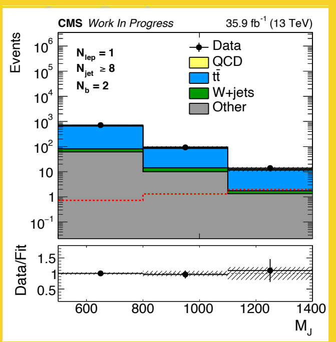
- 5 N_b bins and 3 N_{jet} bins
  - Two high N_b bins are merged for N_{jet} = 4-5 due to limited size of data

Analysis regions

N_b	N_{jet}		
	4-5 (low)	6-7 (med)	≥8 (high)
0	CR	CR	CR
1	CR	CR	CR
2	CR	CR	CR
3	CR	SR	SR
≥4		SR	SR

- 5 N_b bins and 3 N_{jet} bins
  - Two high N_b bins are merged for N_{jet} = 4-5 due to limited size of data
- Control region (CR) and signal region (SR) are defined as shown in the table
- Low N_{jet}, low N_b region is used to validate the analysis procedure and to constrain systematic uncertainties
- Sensitivity is driven by $N_{jet} \geq 8$ and $N_b \geq 3$ bins

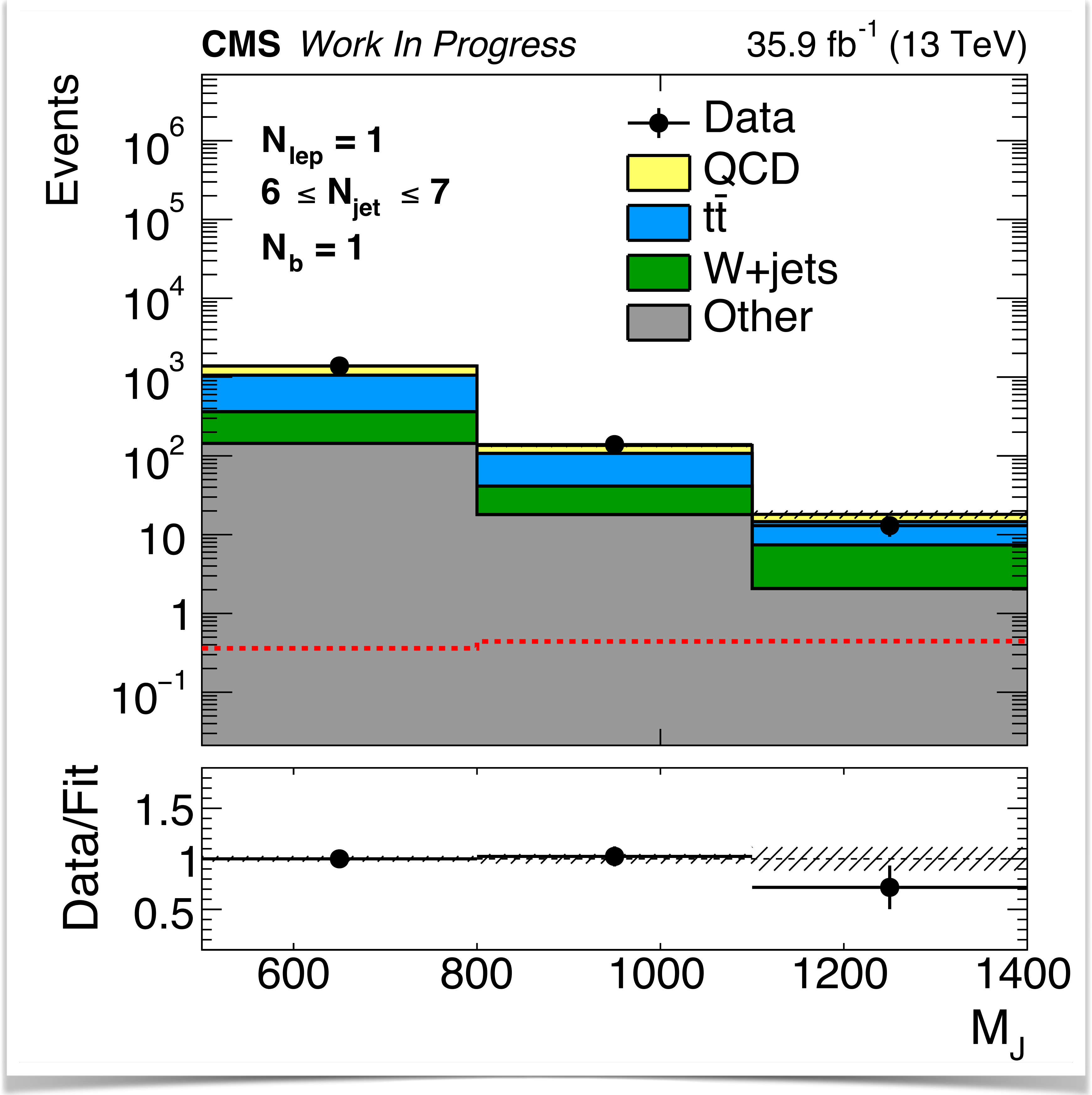
Analysis regions

N_b	N_{jet}		
	4-5 (low)	6-7 (med)	≥8 (high)
0			
1			
2			
3			
≥4			

- 5 N_b bins and 3 N_{jet} bins
  - Two high N_b bins are merged for N_{jet} = 4-5 due to limited size of data
- Control region (CR) and signal region (SR) are defined as shown in the table
- Low N_{jet}, low N_b region is used to validate the analysis procedure and to constrain systematic uncertainties
- Sensitivity is driven by $N_{jet} \geq 8$ and $N_b \geq 3$ bins
- Fit M_J distributions (templates) simultaneously across (N_{jet}, N_b) bins

How normalization is determined (global fit)

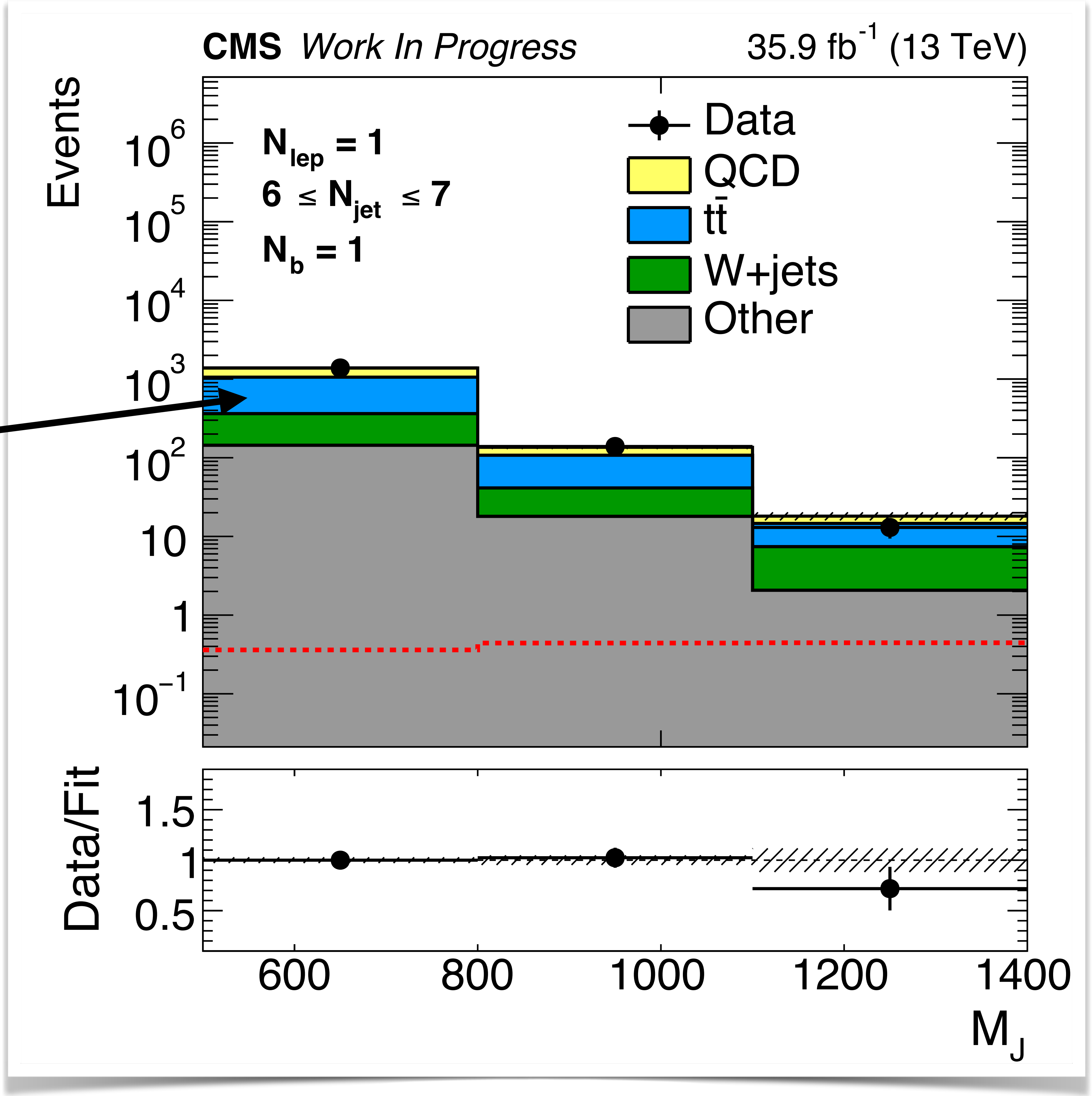
- M_J templates for each process are taken from simulation



How normalization is determined (global fit)

- M_J templates for each process are taken from simulation

- $t\bar{t}$ **normalization** is determined using the total yield in each (N_b,N_{jet}) bin (dominated by 500<M_J <800 GeV)

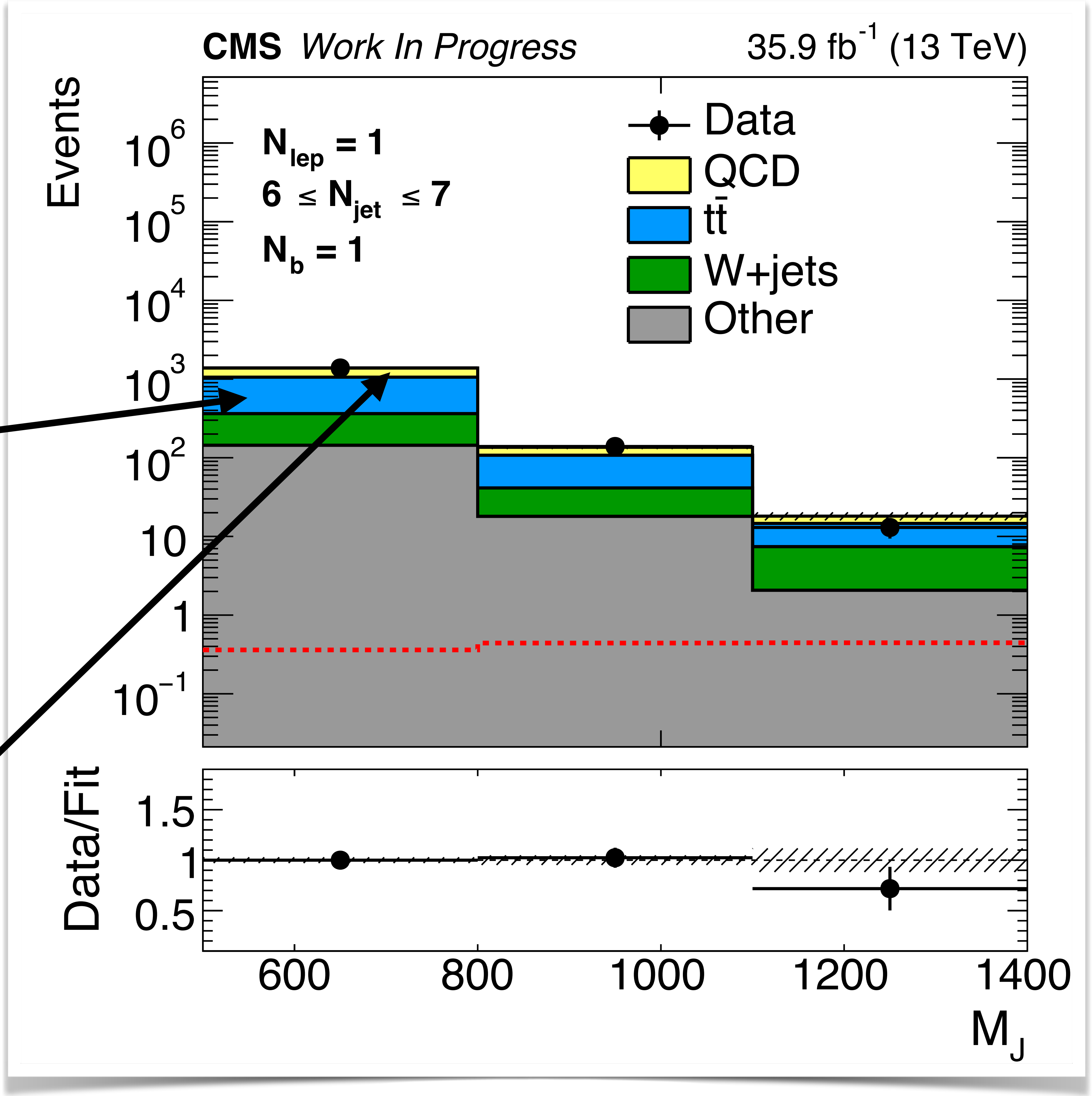


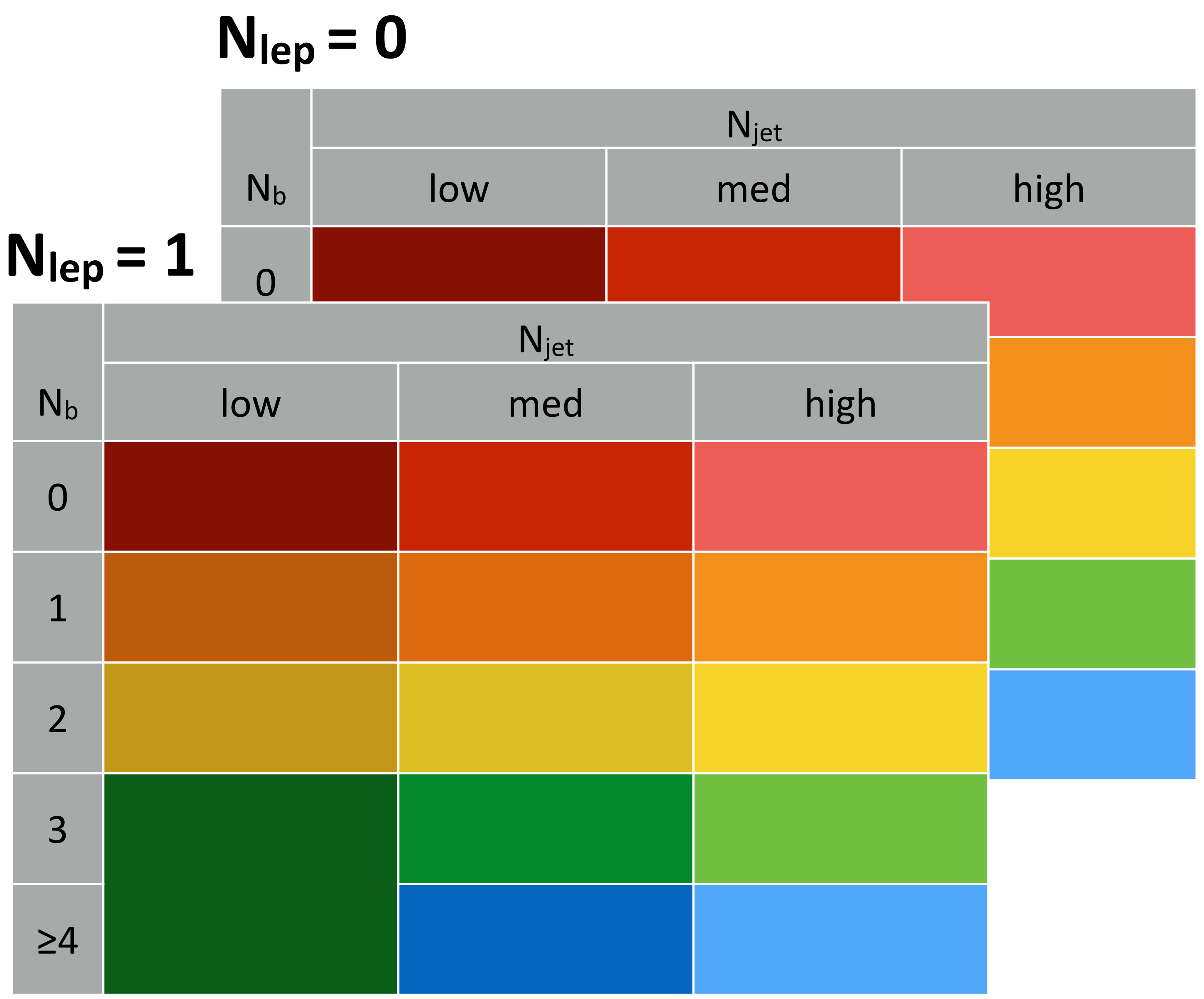
How normalization is determined (global fit)

- M_J templates for each process are taken from simulation

- $t\bar{t}$ **normalization** is determined using the total yield in each (N_b,N_{jet}) bin (dominated by 500<M_J <800 GeV)

- **QCD normalization** is determined by 0-lepton region for each (N_b, N_{jet}) bin
- 0-lepton region is included in the simultaneous fit
- Potential mis-modeling of N_{lep} is estimated and incorporated in the fit





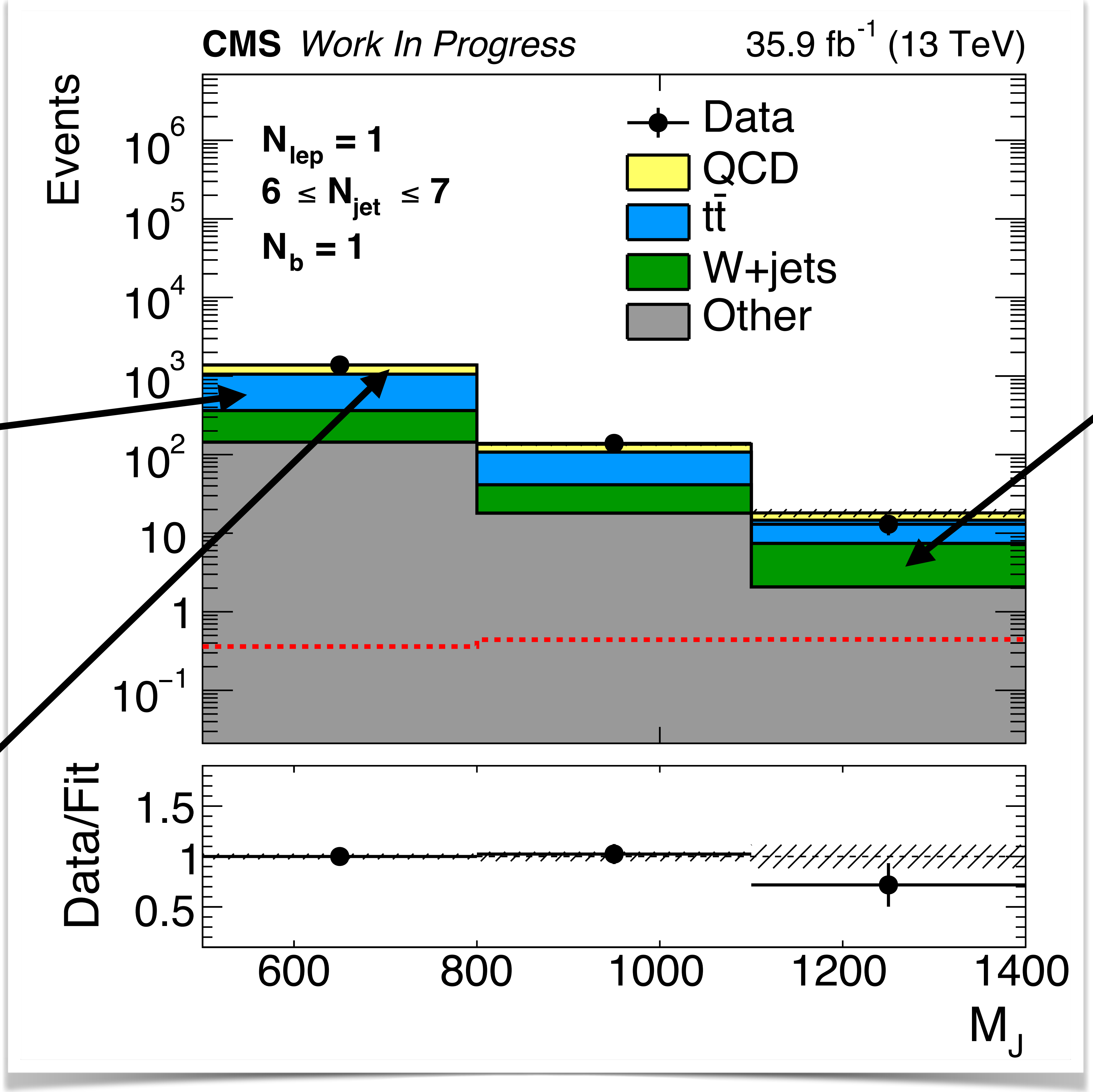
- Copy of (N_b, N_{jet}) bins in N_{lep}=0 region
- Normalization of the bins in the same color moves together

How normalization is determined (global fit)

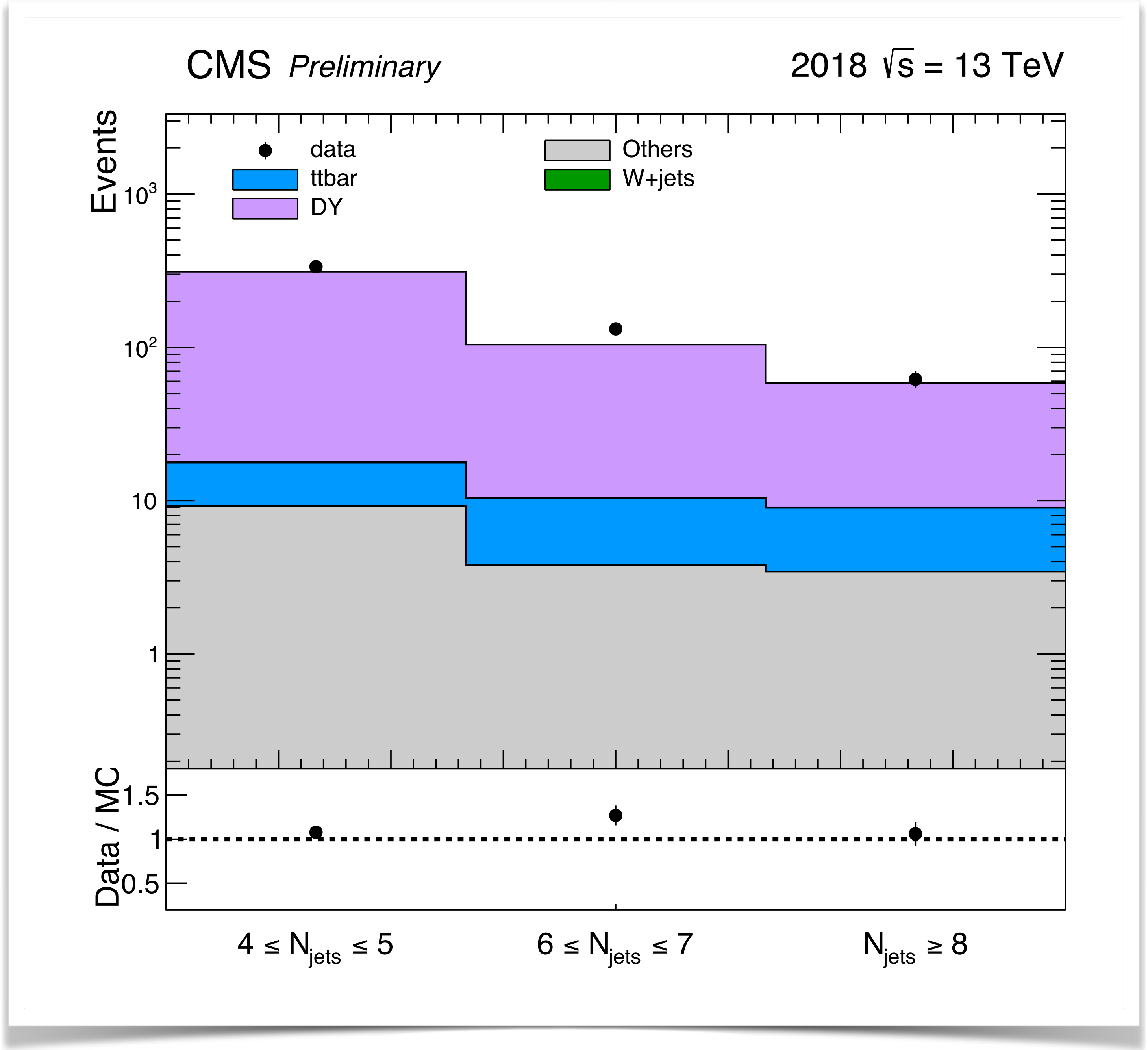
- M_J templates for each process are taken from simulation

- $t\bar{t}$ **normalization** is determined using the total yield in each (N_b,N_{jet}) bin (dominated by 500<M_J <800 GeV)

- **QCD normalization** is determined by 0-lepton region for each (N_b, N_{jet}) bin
- 0-lepton region is included in the simultaneous fit
- Potential mis-modeling of N_{lep} is estimated and incorporated in the fit



- **Wjets normalization** is determined by a global normalization parameter largely constrained by low N_b bins
- Relative normalizations between N_{jet} bins are allowed to change based on the constraints measured in Drell-Yan sample

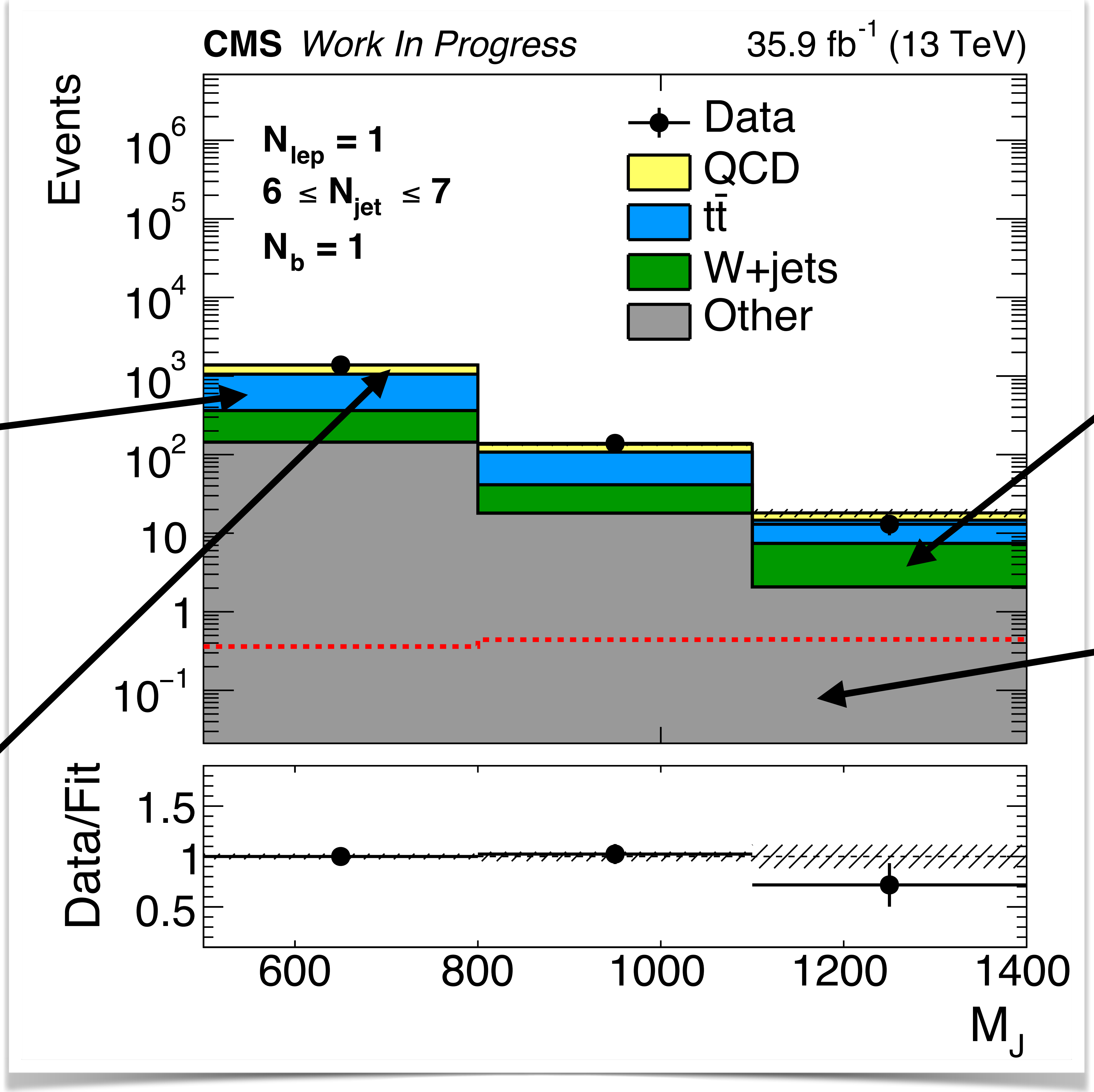


How normalization is determined (global fit)

- M_J templates for each process are taken from simulation

- $t\bar{t}$ **normalization** is determined using the total yield in each (N_b,N_{jet}) bin (dominated by 500<M_J <800 GeV)

- **QCD normalization** is determined by 0-lepton region for each (N_b, N_{jet}) bin
- 0-lepton region is included in the simultaneous fit
- Potential mis-modeling of N_{lep} is estimated and incorporated in the fit



- **Wjets normalization** is determined by a global normalization parameter largely constrained by low N_b bins
- Relative normalizations between N_{jet} bins are allowed to change based on the constraints measured in Drell-Yan sample

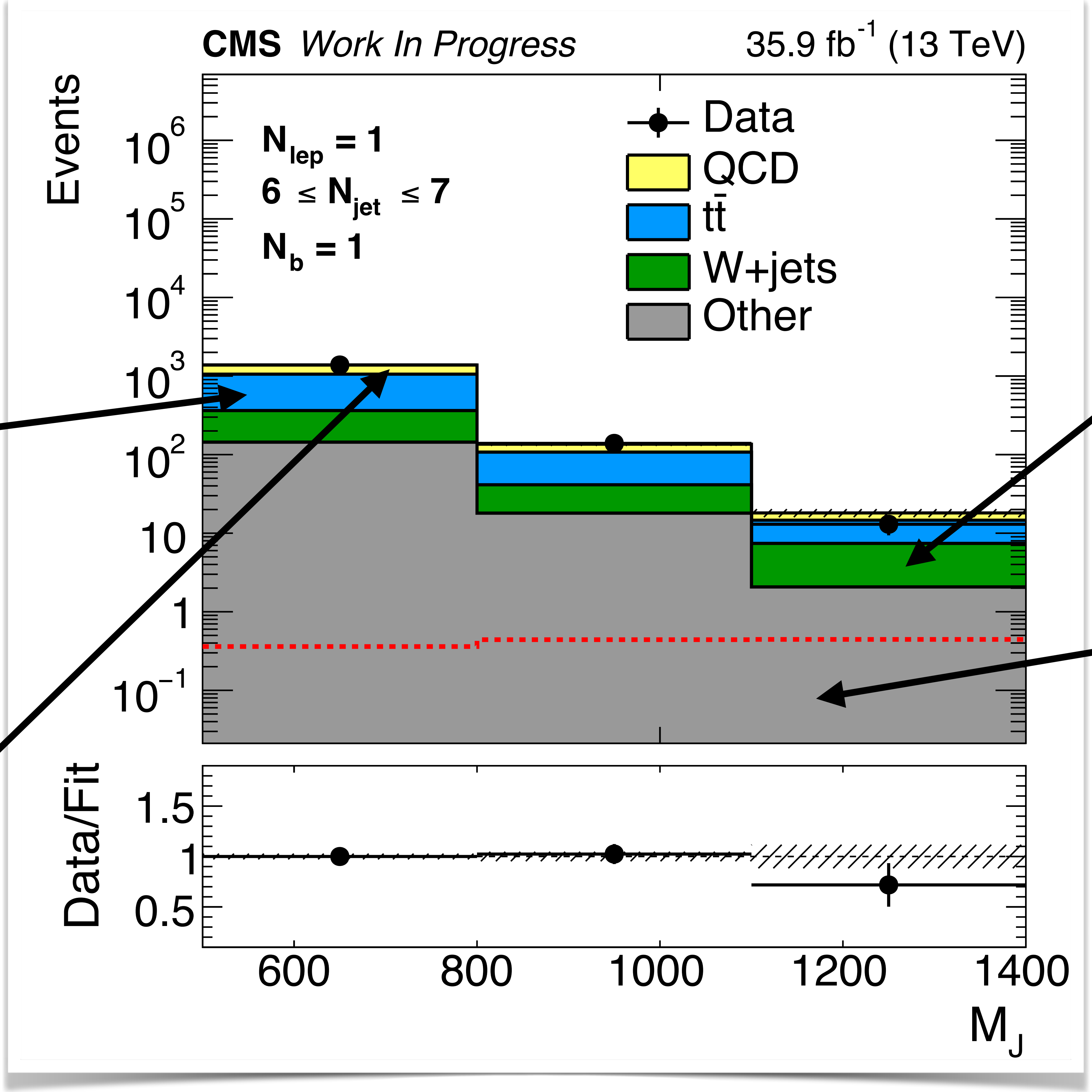
- Estimated from simulation

How normalization is determined (global fit)

- M_J templates for each process are taken from simulation

- $t\bar{t}$ **normalization** is determined using the total yield in each (N_b,N_{jet}) bin (dominated by 500<M_J <800 GeV)

- **QCD normalization** is determined by 0-lepton region for each (N_b, N_{jet}) bin
- 0-lepton region is included in the simultaneous fit
- Potential mis-modeling of N_{lep} is estimated and incorporated in the fit



- **Wjets normalization** is determined by a global normalization parameter largely constrained by low N_b bins
- Relative normalizations between N_{jet} bins are allowed to change based on the constraints measured in Drell-Yan sample

- Estimated from simulation

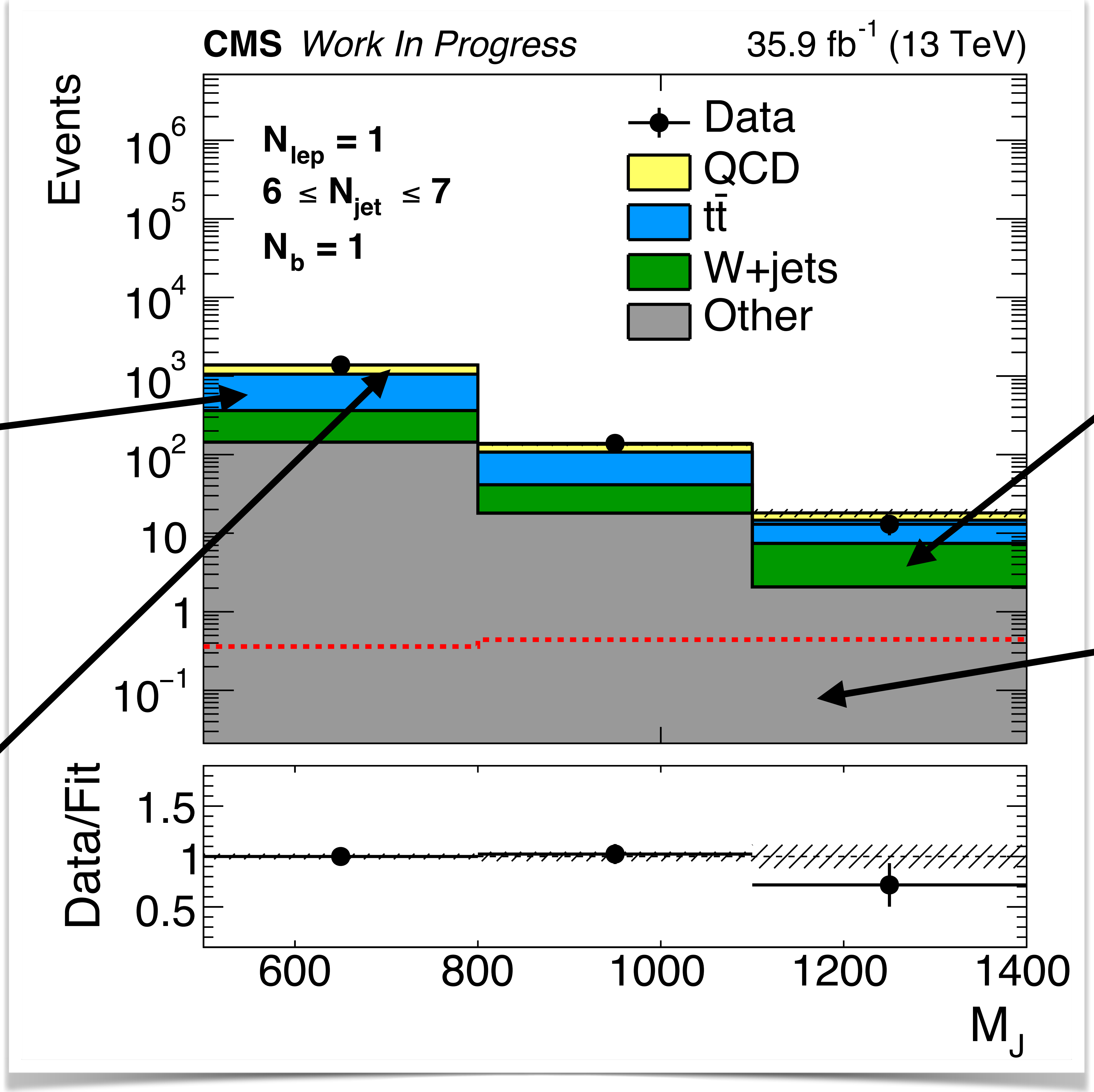
In summary, normalizations of the major backgrounds are determined by data in the global fit

How normalization is determined (global fit)

- M_J templates for each process are taken from simulation

- ***$t\bar{t}$* normalization** is determined using the total yield in each (N_b,N_{jet}) bin (dominated by 500<M_J <800 GeV)

- **QCD normalization** is determined by 0-lepton region for each (N_b, N_{jet}) bin
- 0-lepton region is included in the simultaneous fit
- Potential mis-modeling of N_{lep} is estimated and incorporated in the fit

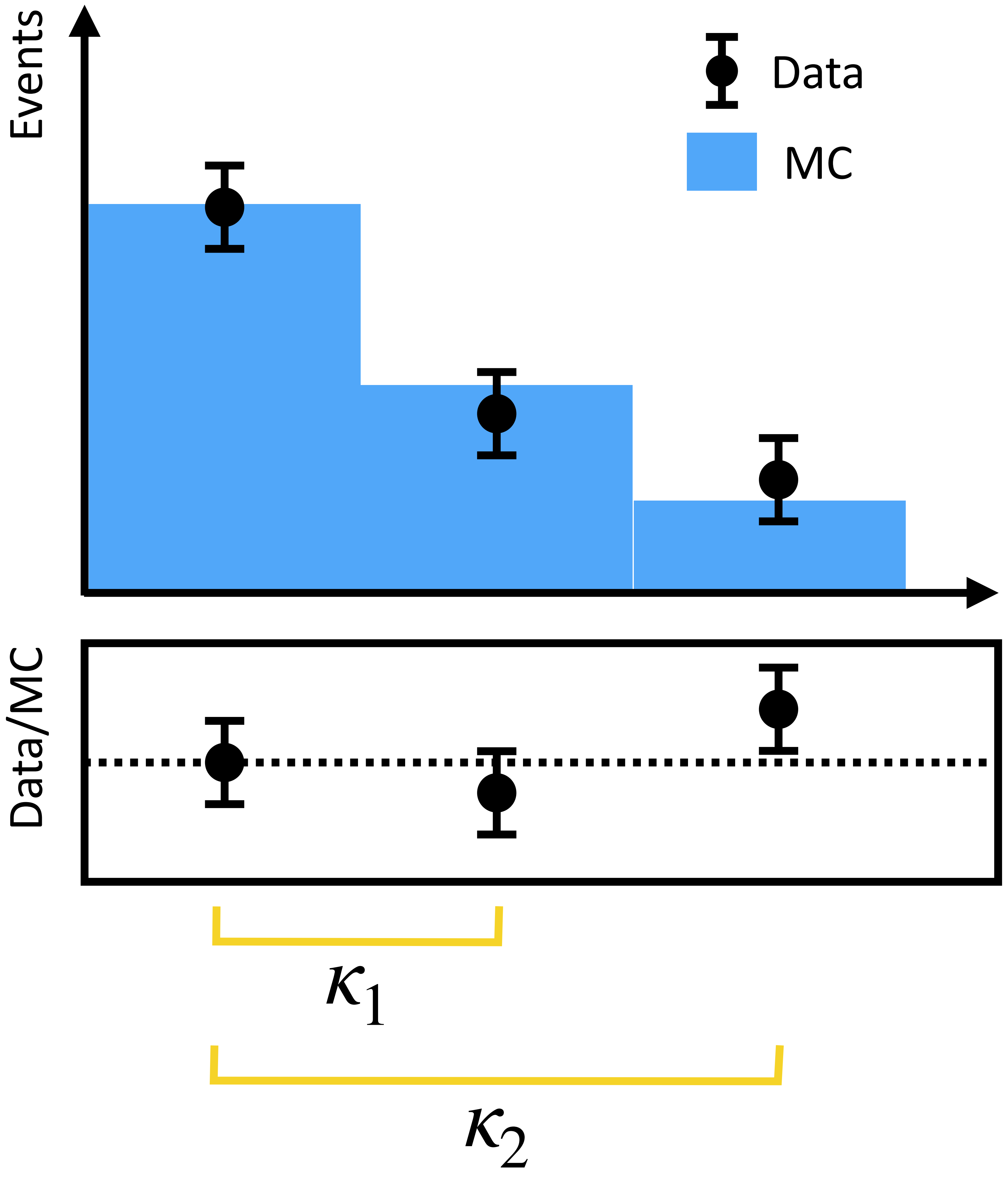


- **Wjets normalization** is determined by a global normalization parameter largely constrained by low N_b bins
- Relative normalizations between N_{jet} bins are allowed to change based on the constraints measured in Drell-Yan sample

- Estimated from simulation

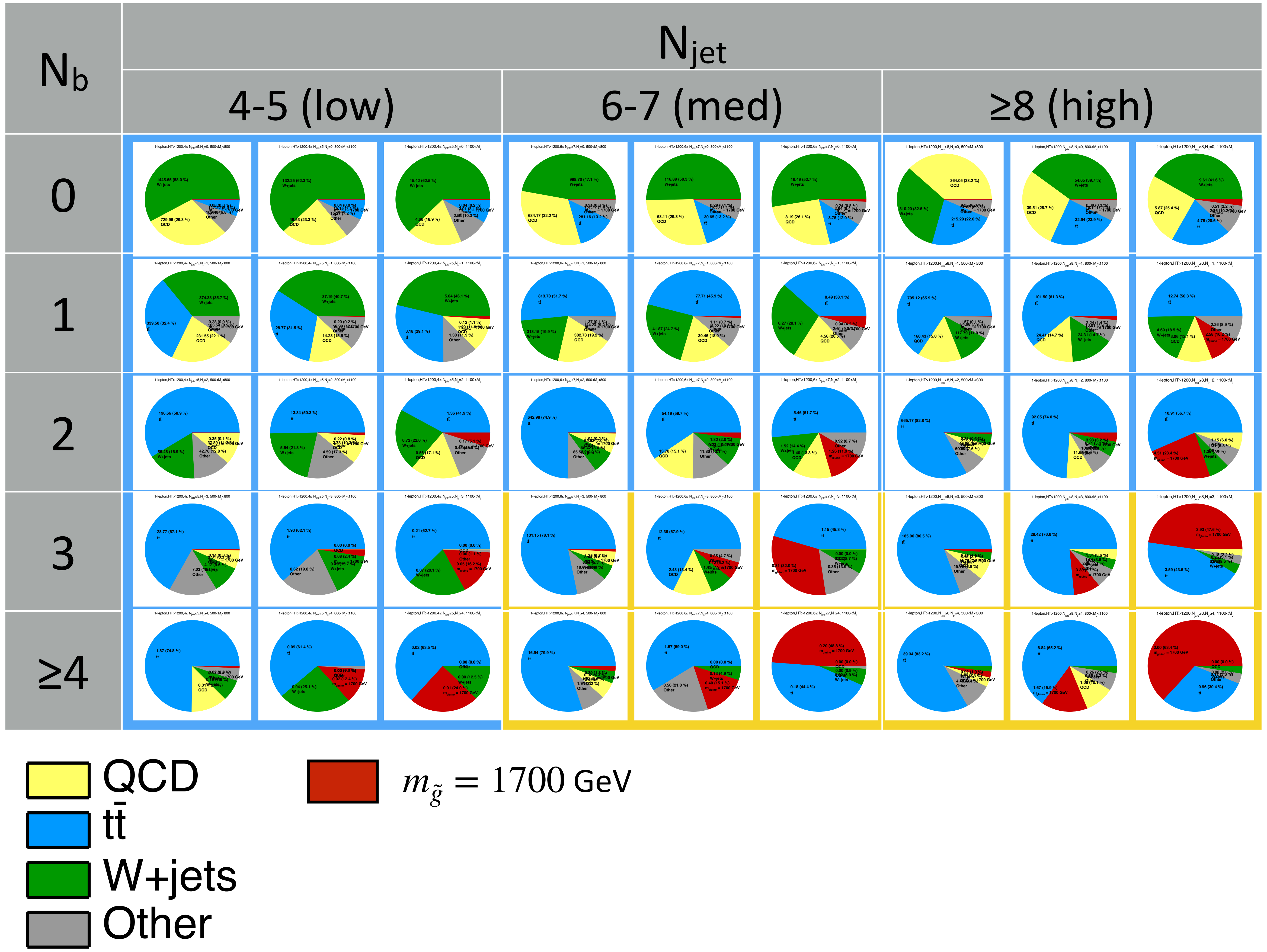
Challenge: correcting potential mis-modeling of M_J shape

M_J shape correction using data



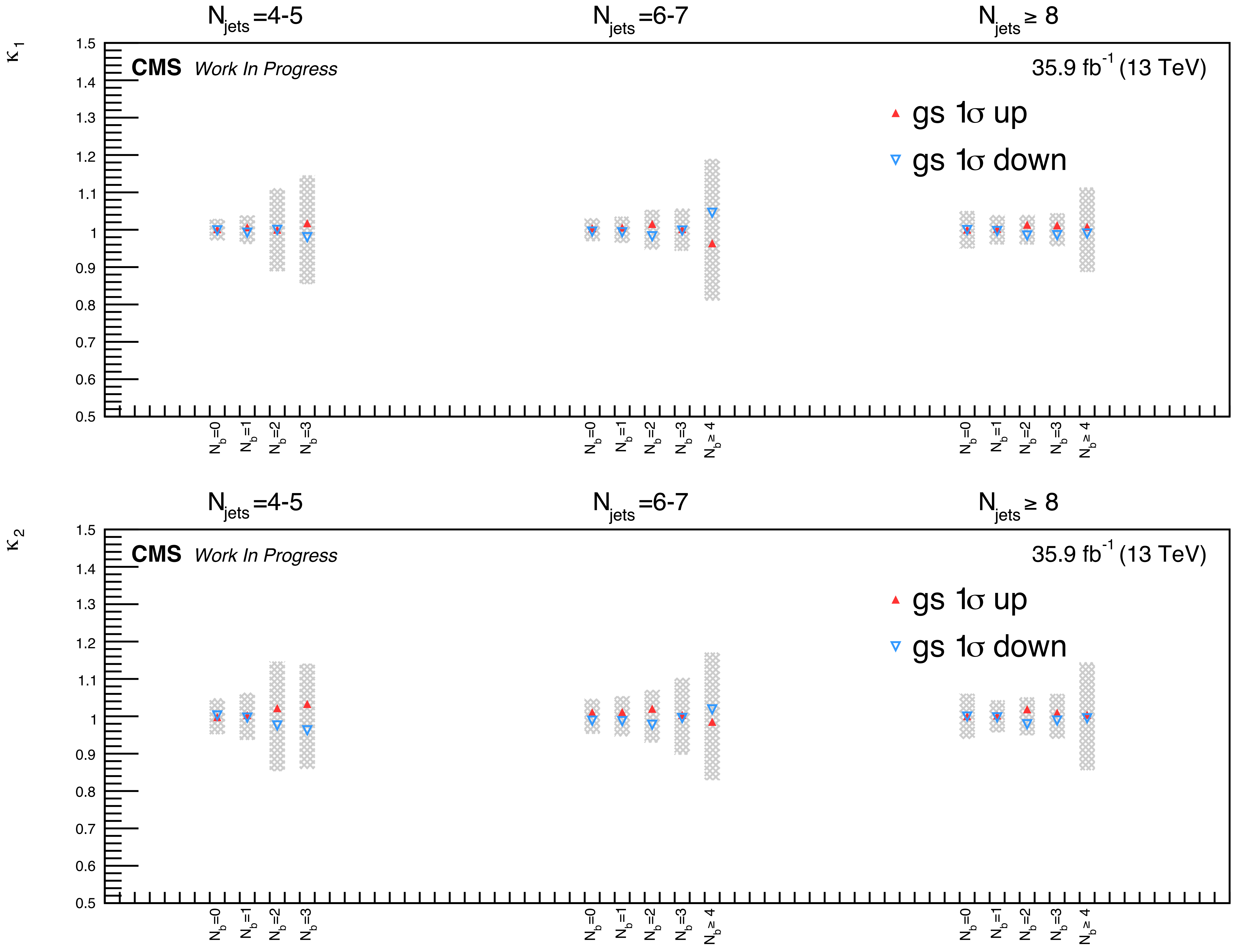
- Correct M_J templates using data in CR
- κ factors: κ_1 and κ_2 where $\kappa_i = \frac{R_i^{Data}}{R_i^{MC}}$
  - $R_1 = \frac{N_{800<M_J<1100\text{ GeV}}}{N_{500<M_J<800\text{ GeV}}}$ and $R_2 = \frac{N_{M_J>1100\text{ GeV}}}{N_{500<M_J<800\text{ GeV}}}$

M_J shape correction using data



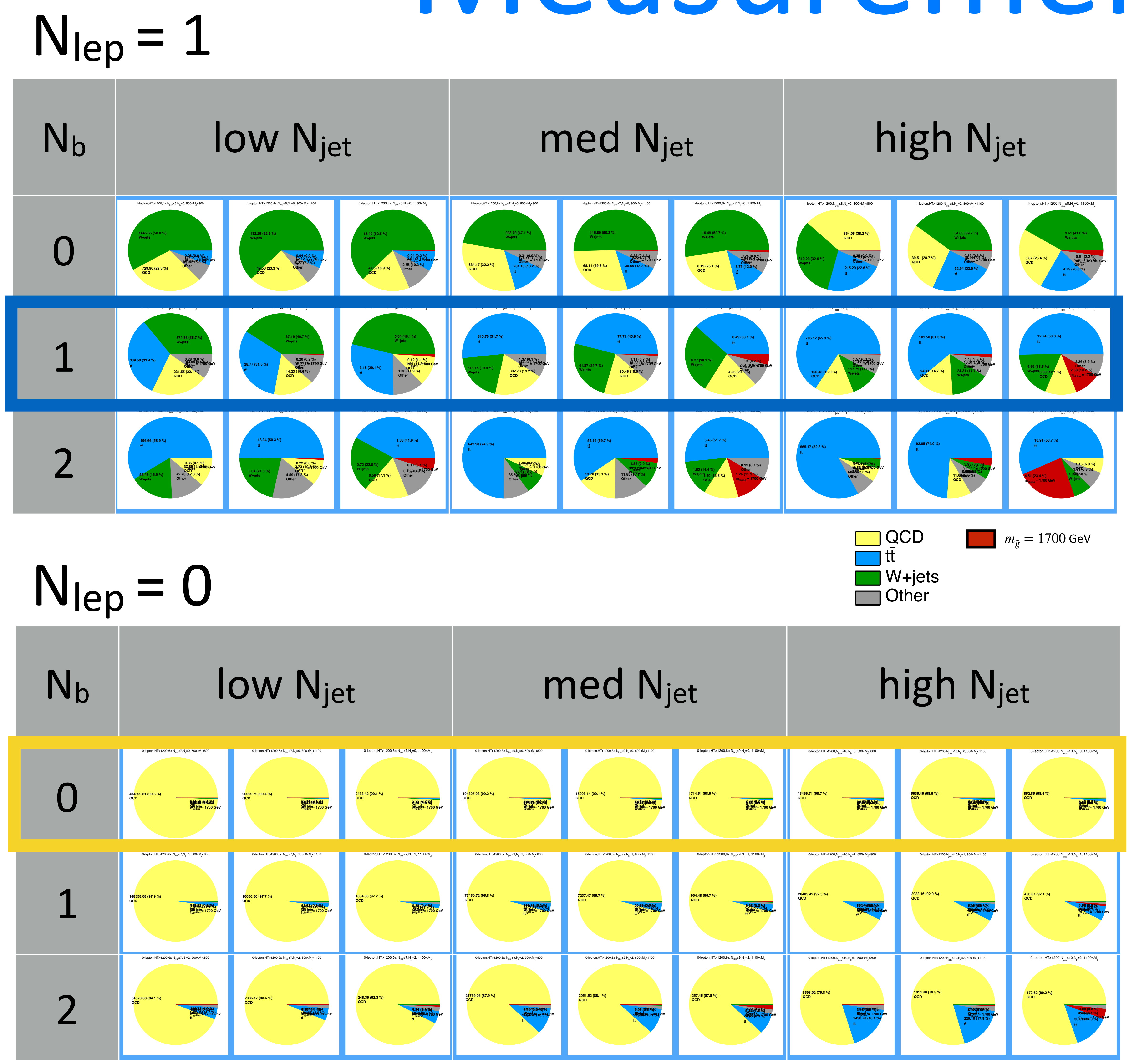
- Correct M_J templates using data in CR
- κ factors: κ_1 and κ_2 where $\kappa_i = \dfrac{R_i^{Data}}{R_i^{MC}}$
- $R_1 = \dfrac{N_{800<M_J<1100\text{ GeV}}}{N_{500<M_J<800\text{ GeV}}}$ and $R_2 = \dfrac{N_{M_J>1100\text{ GeV}}}{N_{500<M_J<800\text{ GeV}}}$
- Then, let the fit determine κ factors using low N_b bins
  - κ factors in low and high N_b bins should be consistent
- Check this using MC by imposing systematic effects

Independence of κ factors on N_b in MC



- Impose gluon-splitting up/down variations to MC and take it as data, then calculate κ factors
- κ factors are consistent across N_b bins
- Have checked other systematic effects and drawn the same conclusion

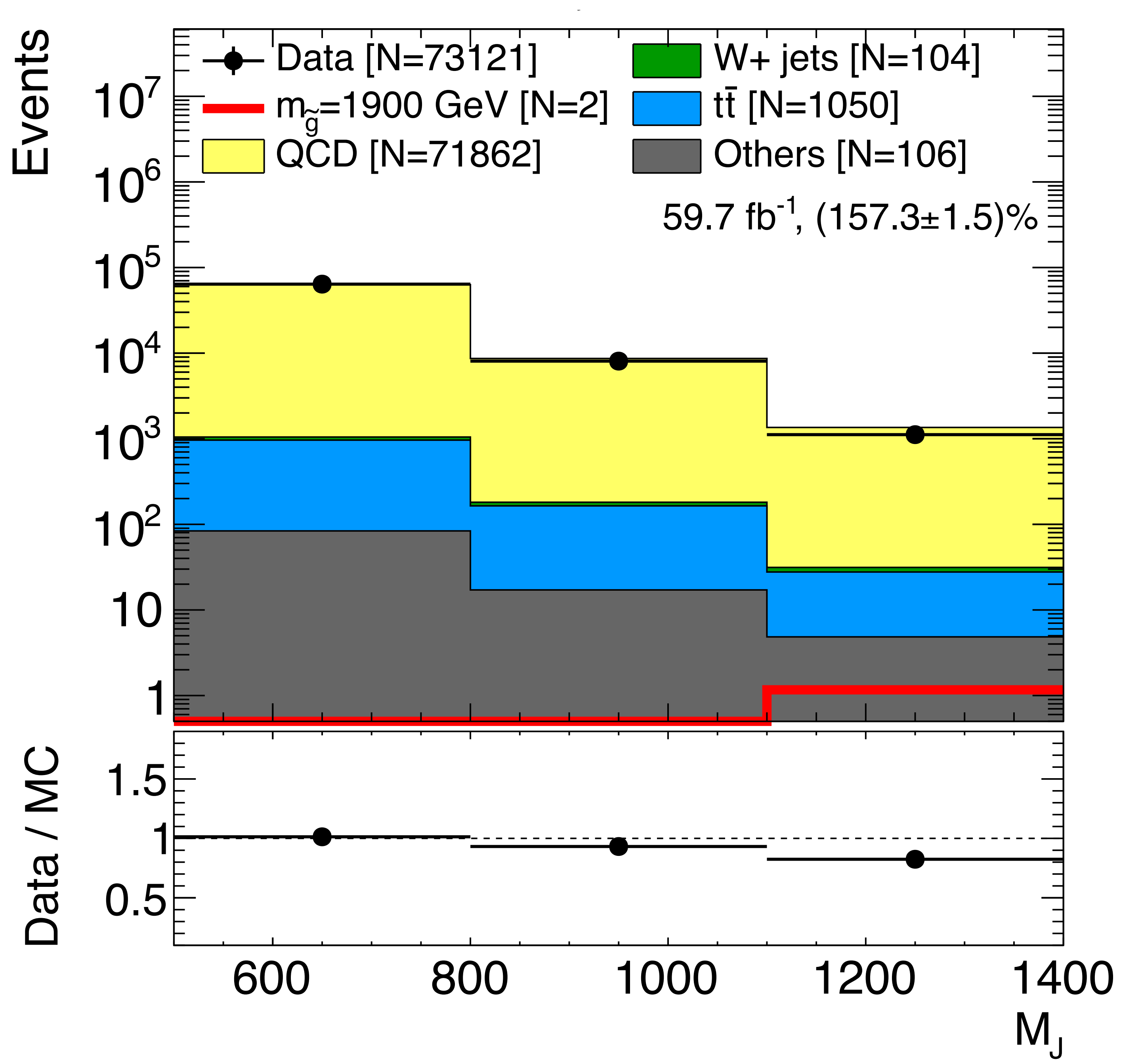
Measurement of κ factors



- κ factors are constrained by CR in the global fit
  - Need reasonable range ($\sigma_{1/2}^{t\bar{t}}$, $\sigma_{1/2}^{QCD}$, and $\sigma_{1/2}^{Wjets}$) as input
- Measure κ factors in independent regions
  - Not try to measure them precisely but to estimate some conservative range
- Use separate κ factors for the main backgrounds ($t\bar{t}$, QCD, and Wjets)
- Measurement regions
  - $t\bar{t}$: $N_{lep} = 1$, $N_b = 1$
  - QCD: $N_{lep} = 0$, $N_b = 0$
  - Wjets: DY region

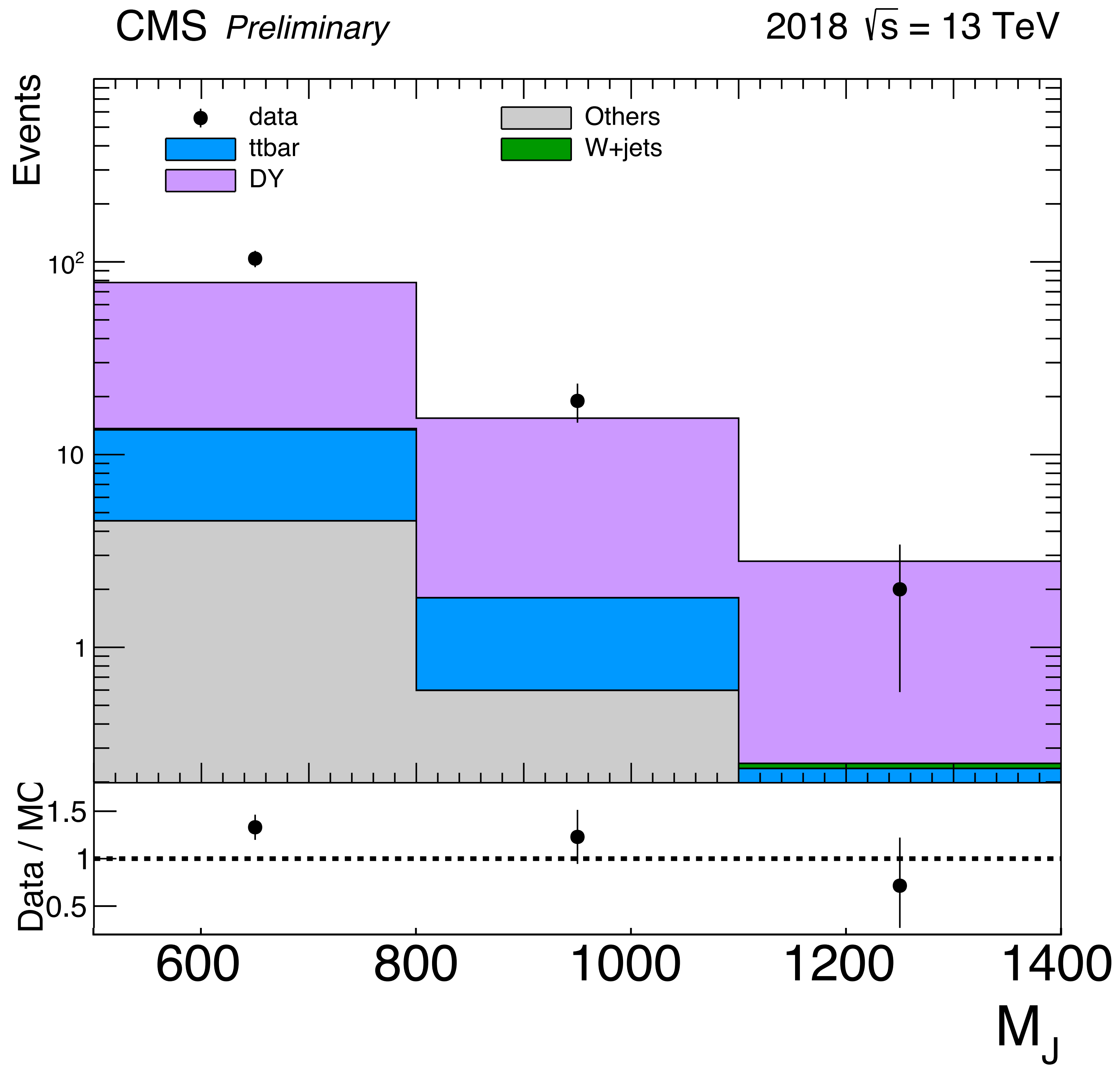
Measurement of κ factors

κ^{QCD} measurements



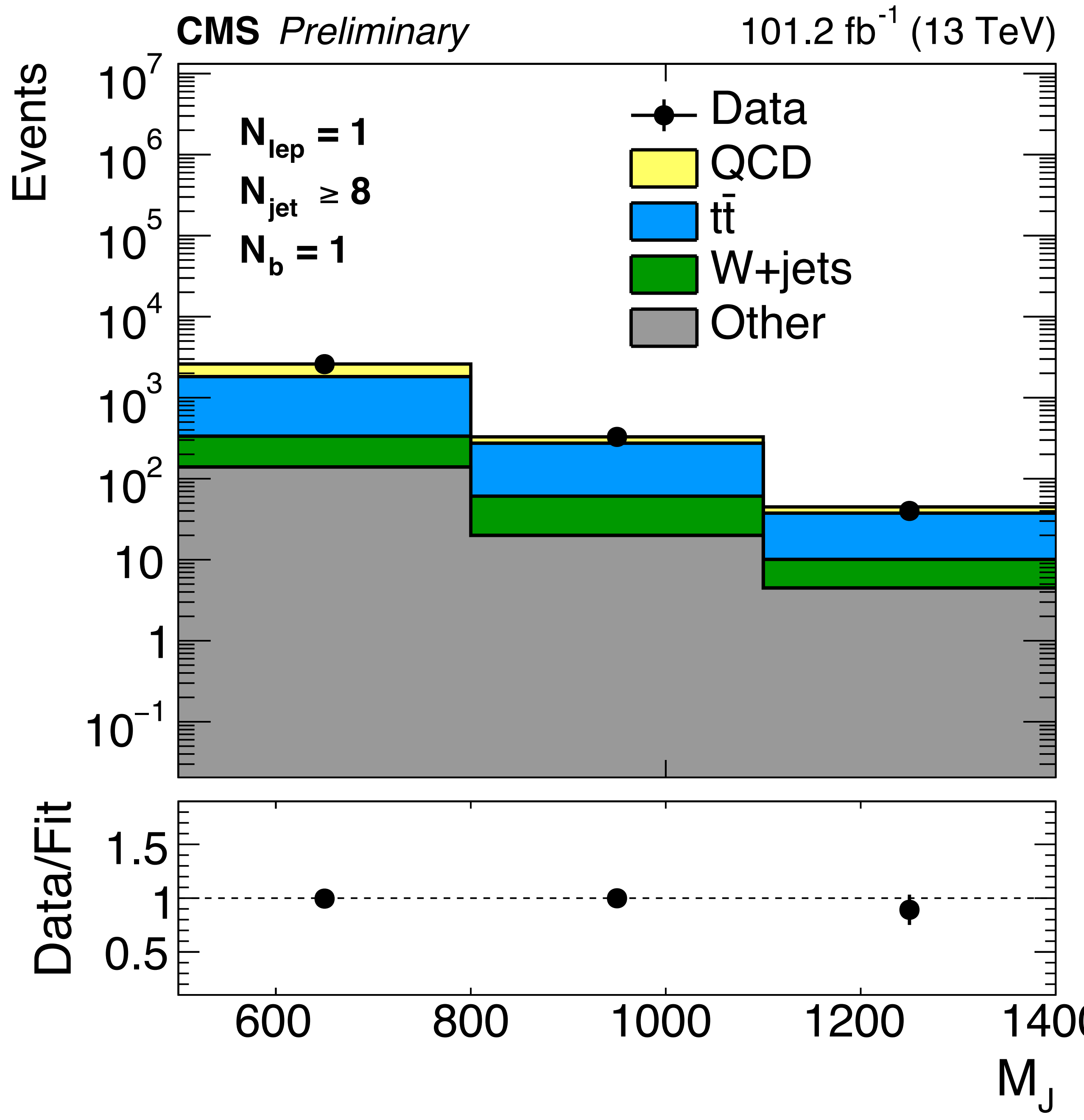
- N_{lep} = 0, N_b = 0 region
- High purity and large stats

κ^{Wjets} measurements



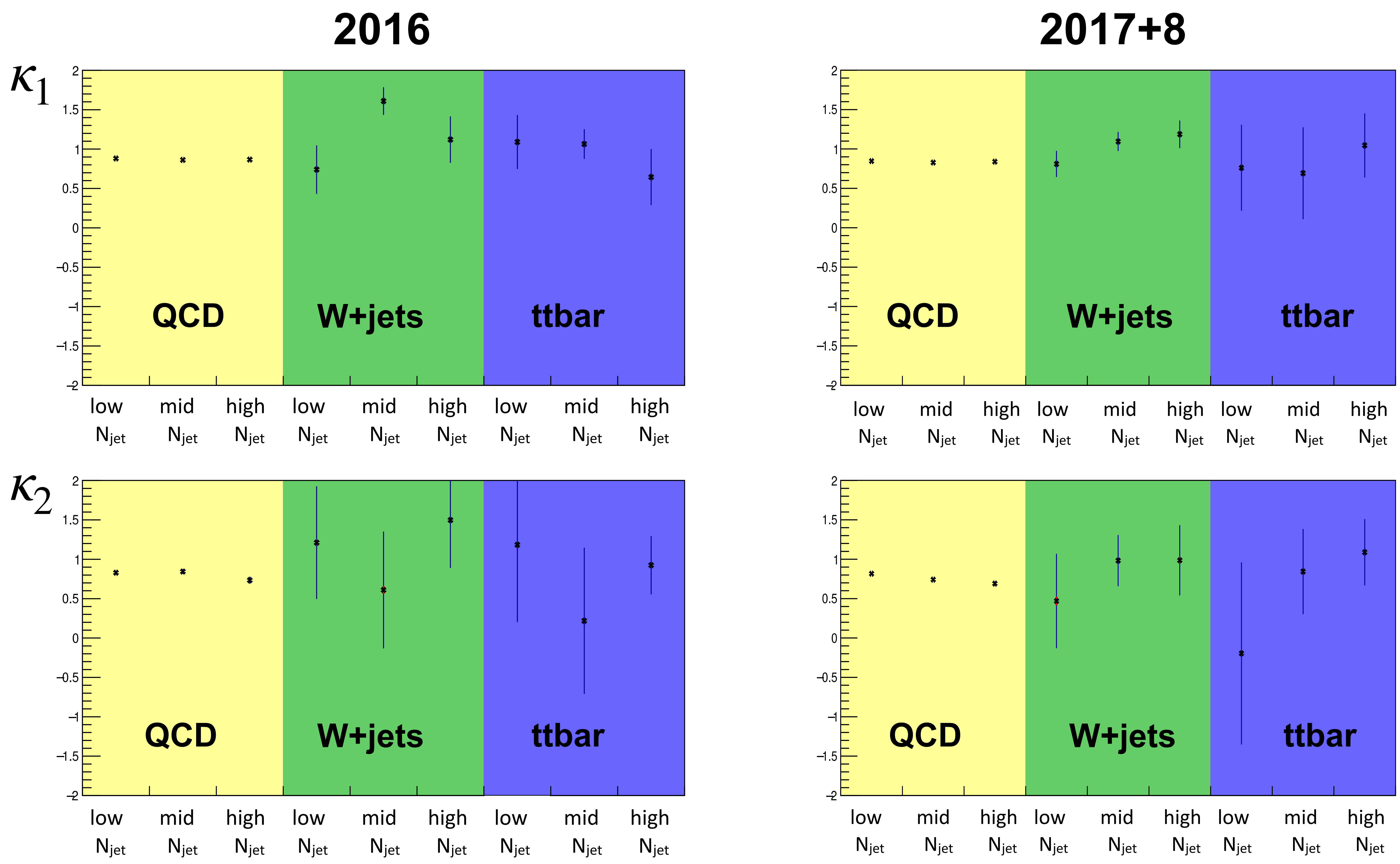
- DY and Wjets are kinematically similar
  → Measure $\sigma_{1/2}^{Wjets}$ using DY events
- Selection: N_{lep} = 2, 80 < m_{ll} < 100 GeV

$\kappa^{t\bar{t}}$ measurements



- N_{lep} = 1, N_b = 1 region
- Some bins have large contributions from non-$t\bar{t}$ backgrounds
- Correct QCD and W_{jets} M_J shapes before subtraction

Summary of κ factor measurements



- Summary of κ measurements
- For QCD, correct the M_J shapes based on the measurements and the deviation from unity is taken as $\sigma_{1/2}^{QCD}$
- For Wjets and $t\bar{t}$, use the deviation from unity as $\sigma_{1/2}^{Wjets/t\bar{t}}$ (due to limited stats)

Fit validation

N_b	N_{jet}		
	4-5 (low)	6-7 (med)	≥8 (high)
0	CR	CR	CR
1	CR	CR	CR
2	CR	CR	CR
3	CR	SR	SR
≥4		SR	SR

- Now we have all ingredients to perform a global fit
  - Before doing it, test the fit model in two ways
- Inject signal and check whether the fitted signal strength is consistent with the input
  - No bias up to $m_{\tilde{g}} = 2.2$ TeV
- Perform CR fit in stages
  - Step1: $0 \leq N_b \leq 2$ and low and mid N_{jet} region

Fit validation

N_b	N_{jet}		
	4-5 (low)	6-7 (med)	≥8 (high)
0	CR	CR	CR
1	CR	CR	CR
2	CR	CR	CR
3	CR	SR	SR
≥4		SR	SR

- Now we have all ingredients to perform a global fit
  - Before doing it, test the fit model in two ways
- Inject signal and check whether the fitted signal strength is consistent with the input
  - No bias up to $m_{\tilde{g}} = 2.2$ TeV
- Perform CR fit in stages
  - Step1: $0 \leq N_b \leq 2$ and low and mid N_{jet} region
  - Step2: All regions in $0 \leq N_b \leq 2$

Fit validation

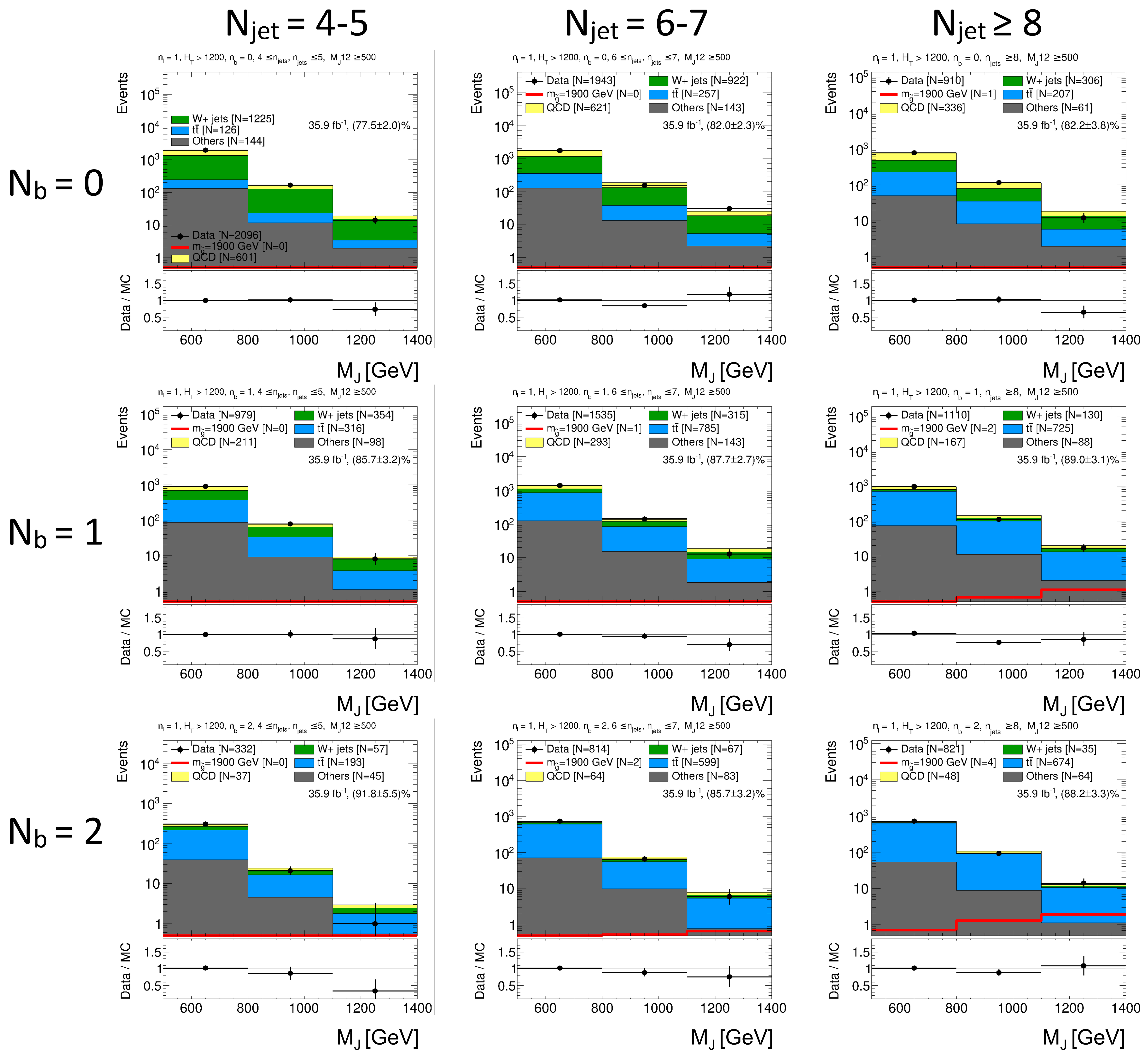
N_b	N_{jet} 4-5 (low)	N_{jet} 6-7 (med)	N_{jet} ≥8 (high)
0	CR	CR	CR
1	CR	CR	CR
2	CR	CR	CR
3	CR	SR	SR
≥4	CR	SR	SR

- Now we have all ingredients to perform a global fit
  - Before doing it, test the fit model in two ways
- Inject signal and check whether the fitted signal strength is consistent with the input
  - No bias up to $m_{\tilde{g}} = 2.2$ TeV
- Perform CR fit in stages
  - Step1: $0 \leq N_b \leq 2$ and low and mid N_{jet} region
  - Step2: All regions in $0 \leq N_b \leq 2$
  - Step3: All regions in $0 \leq N_b \leq 2$ and all N_b regions in low N_{jet} region

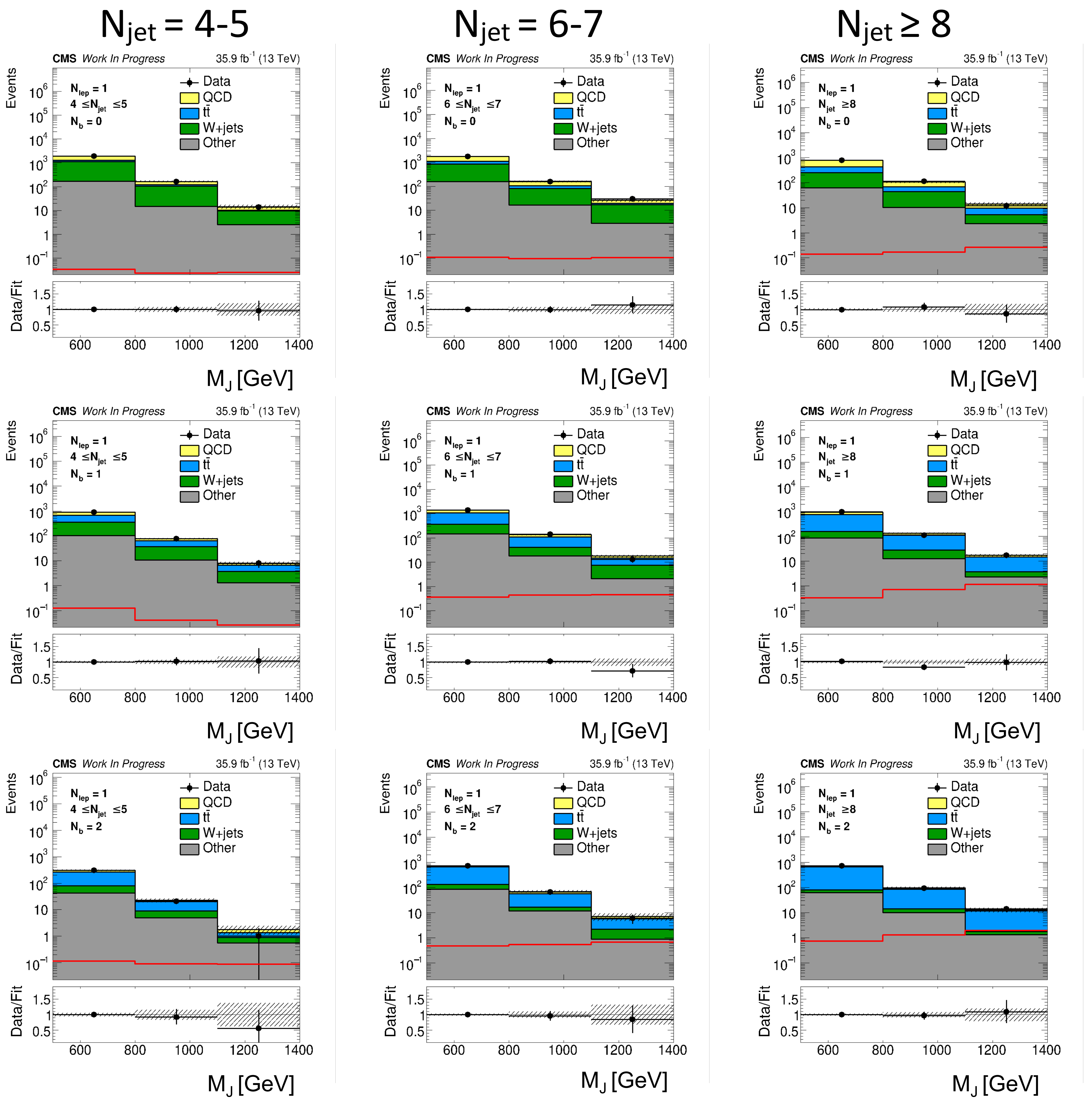
	N_{jet}		
N	4-5 (low)	6-7 (med)	≥8 (high)
0			
1			
2			
3			
≥			

Results of step2: 2016

Pre-fit M_J distributions



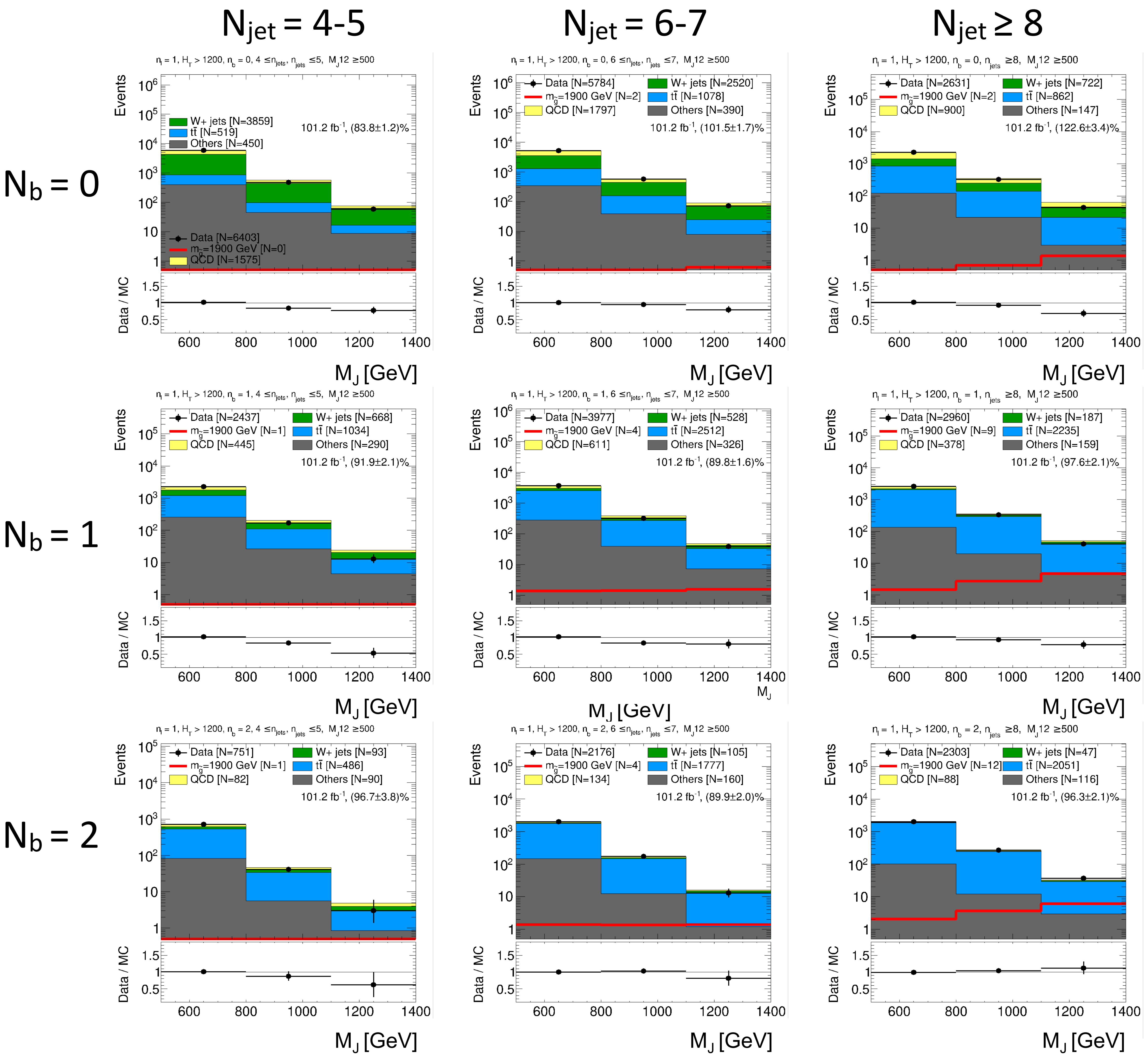
Post-fit M_J distributions



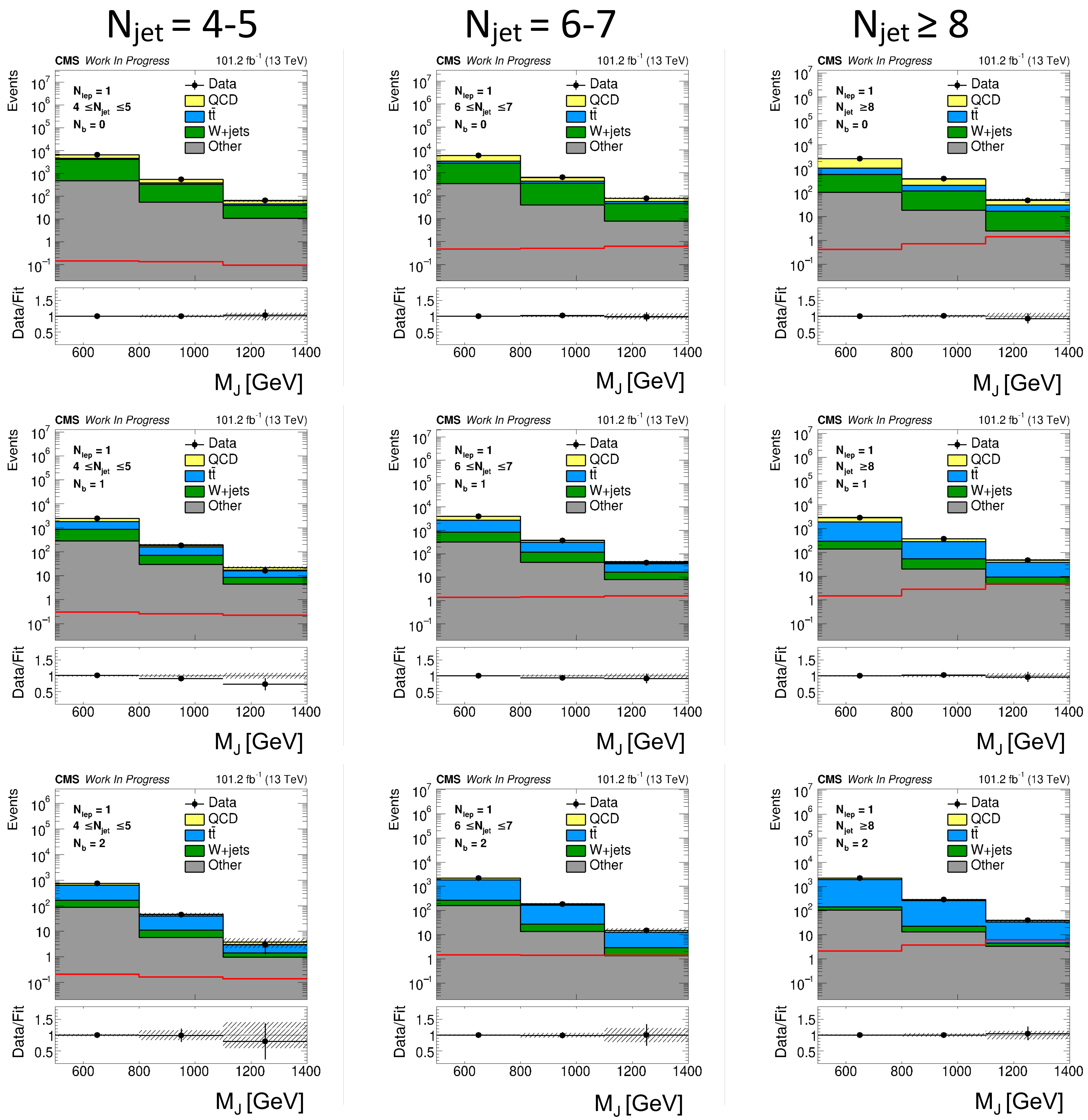
N	N_{jet} 4-5 (low)	6-7 (med)	≥8 (high)
0			
1			
2			
3			
≥			

Results of step2: 2017+2018

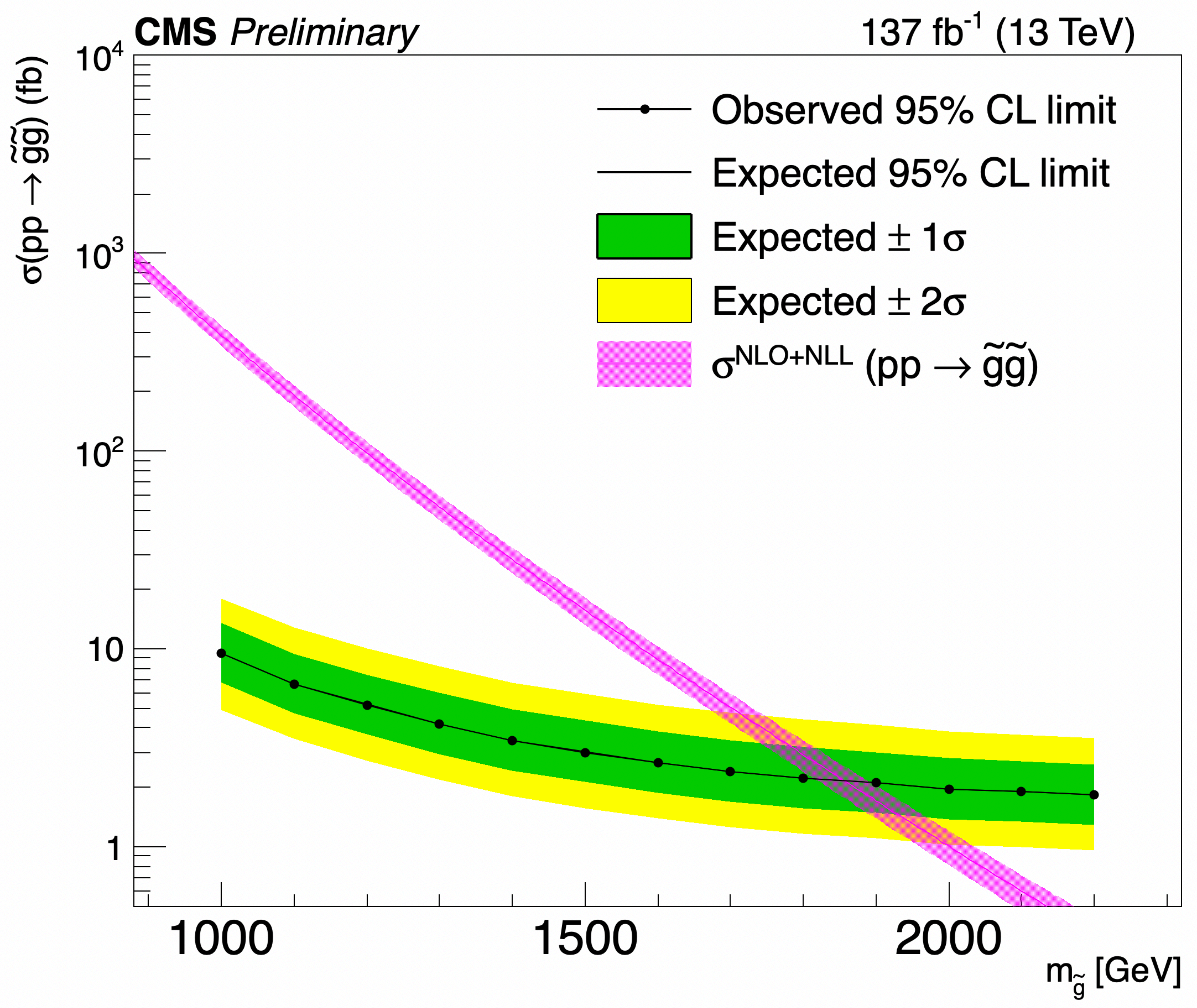
Pre-fit M_J distributions



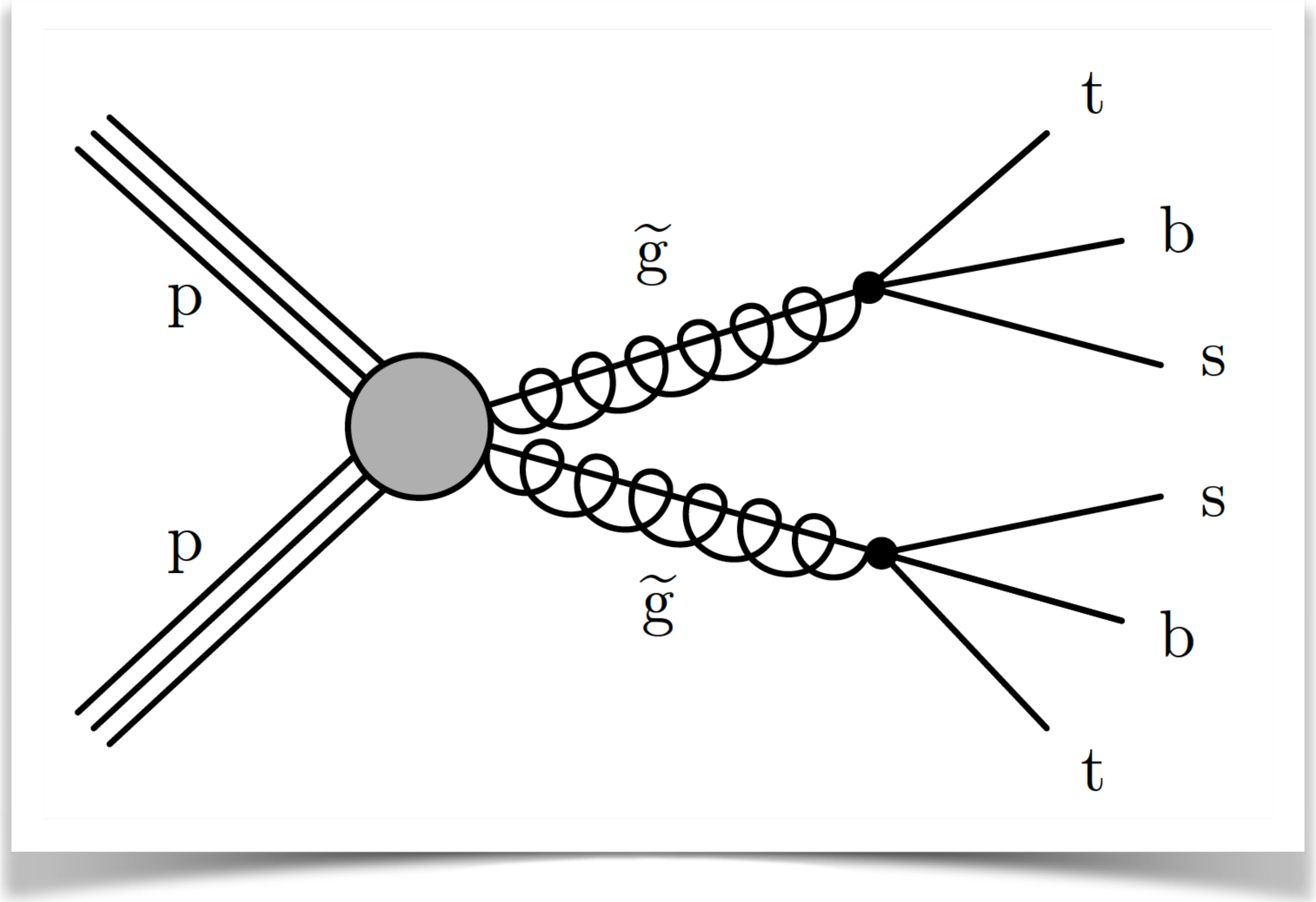
Post-fit M_J distributions



Exclusion limit

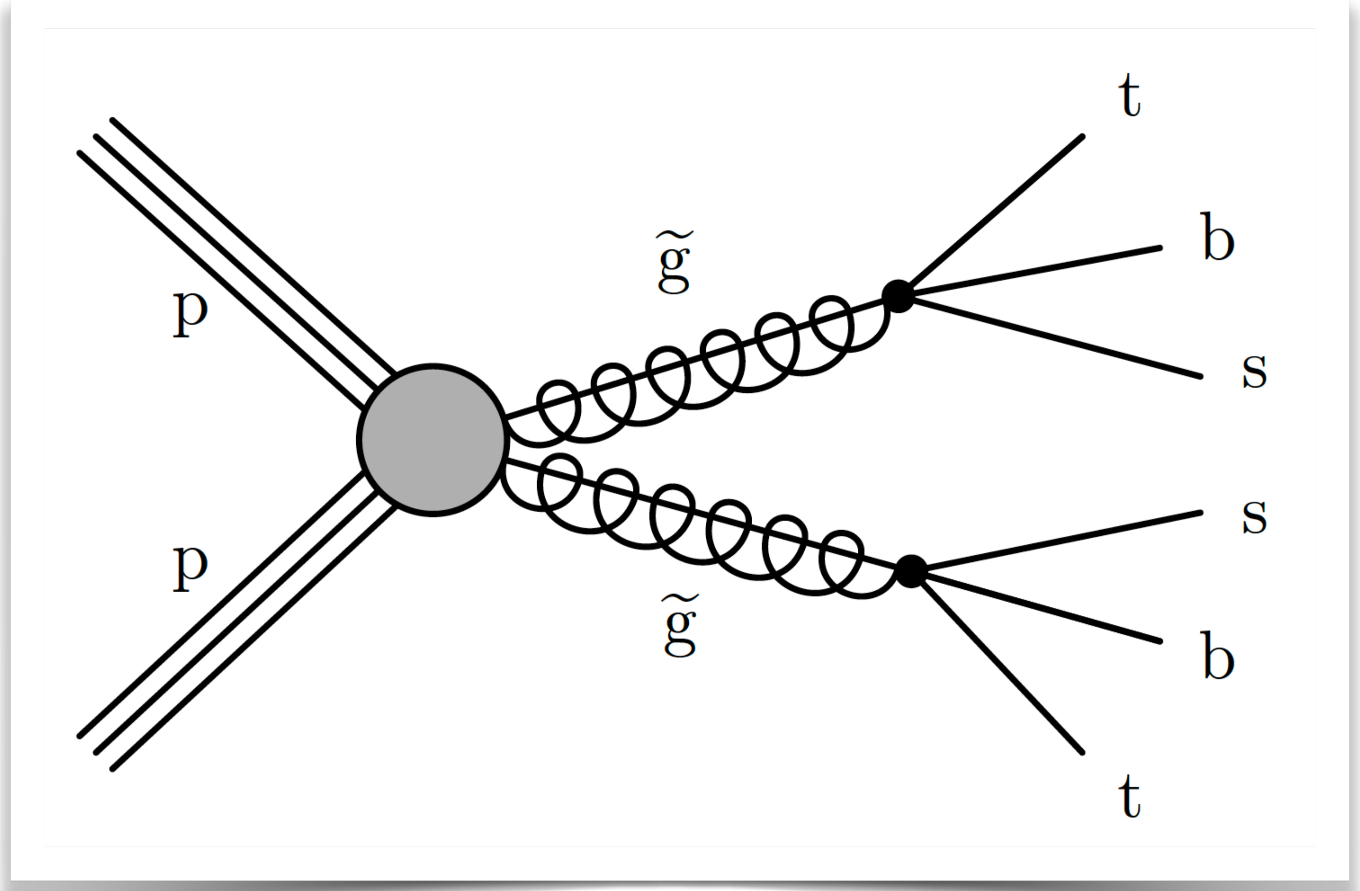


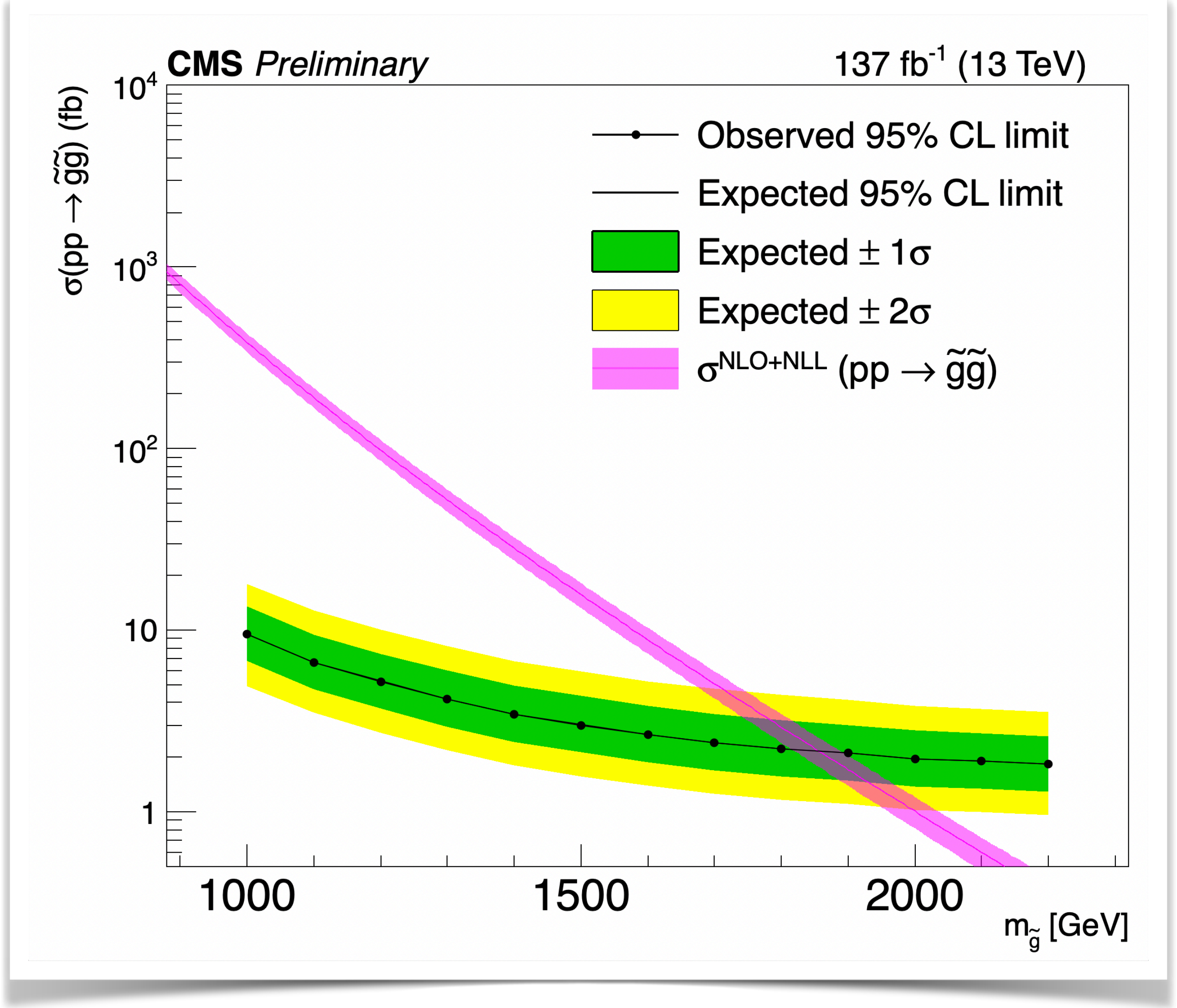
T1tbs



- Expected limit: $m_{\tilde{g}} = 1.85$TeV
  - About 200 GeV improvement compared to the 2016 results

Summary - RPV SUSY





- RPV SUSY can evade the constraints from RPC SUSY searches by allowing LSP to decay to SM particles resulting in signatures without MET
- CMS is performing a search in the single-lepton final state targeting gluino pair production where gluino decays to tbs
- Data-driven analysis that is insensitive to background modeling
- With full Run2 data, expect to set the limit of 1850 GeV at 95% CL for gluino mass

Motivation

Ref: https://en.wikipedia.org/wiki/Oil_drop_experiment

Oil drop experiment apparatus

Robert Millikan

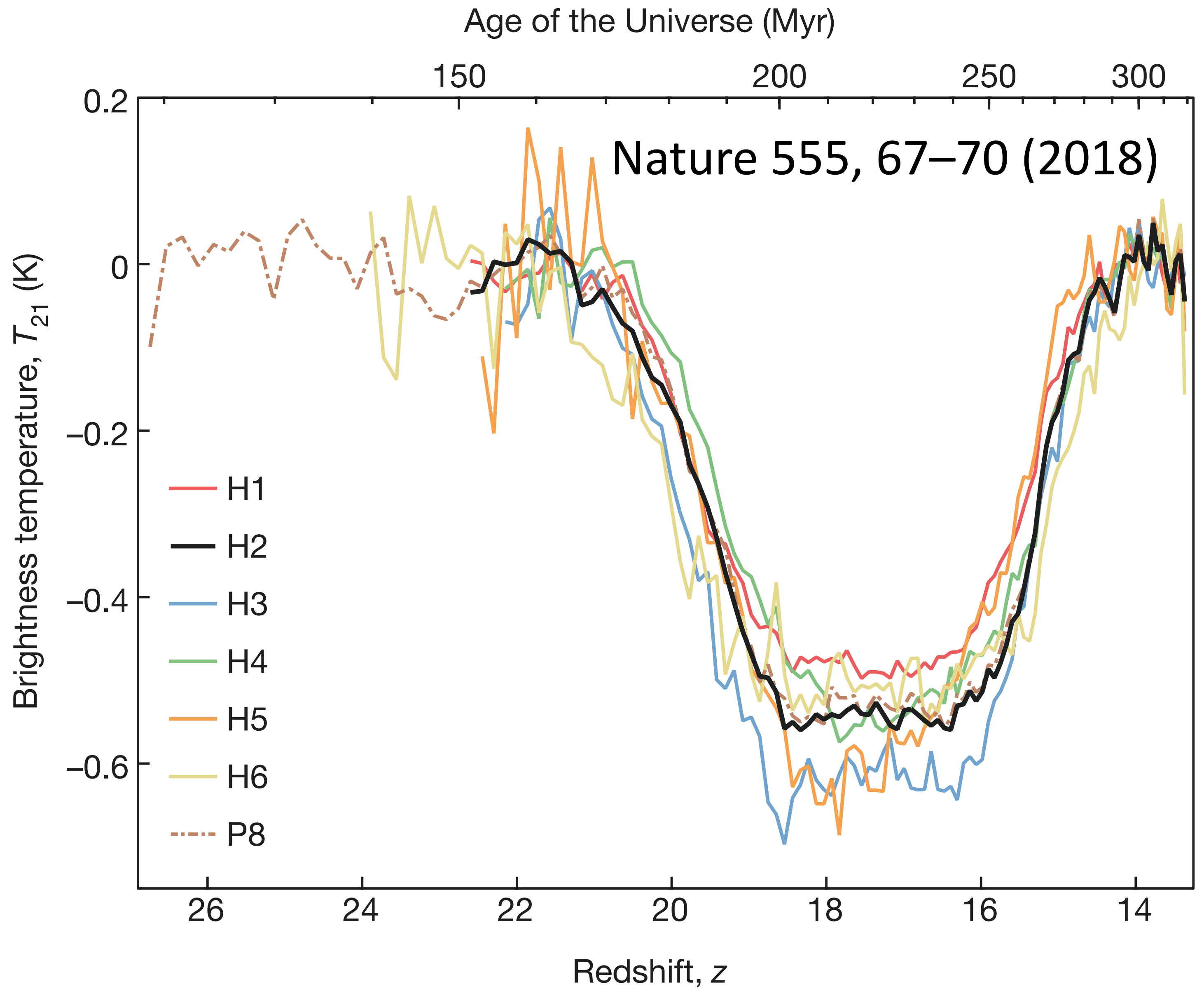


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

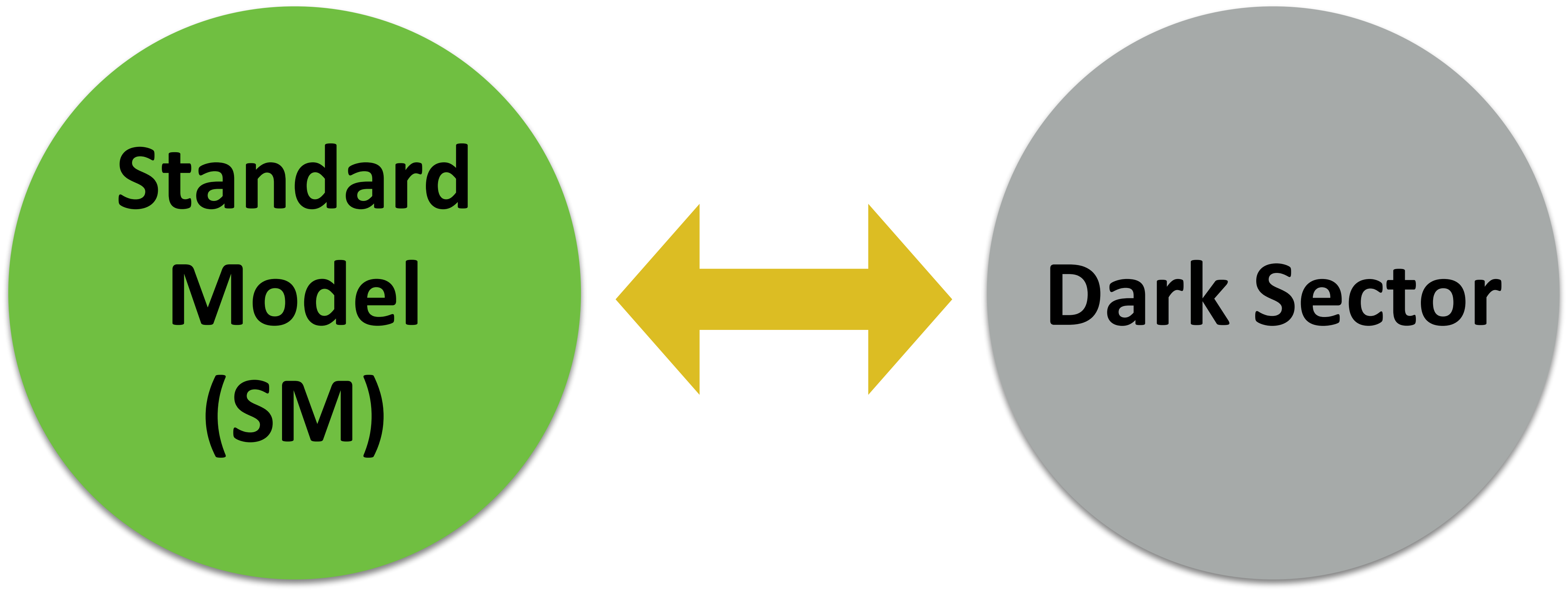
- Since its discovery in Robert Millikan's oil drop experiment, electric charge quantization is a long-standing question in particle physics
- Well-motivated dark-sector models have been proposed to predict the existence of millicharged particles (mCPs, χs) while preserving the possibility for unification
  - Such models can contain a rich internal structure, providing candidate particles for dark matter
- Results of EDGES experiment [*Nature* 555, 67–70 (2018)] can be explained if a fraction of DM is millicharged

Millicharged particles

- There are multiple ways to get mili-charged particles
- A new U(1) in dark sector with massless dark-photon (A') and massive dark-fermion (ψ)

$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not{\partial} + ie'\not{A}' + iM_{\text{mCP}}\right)\psi$$

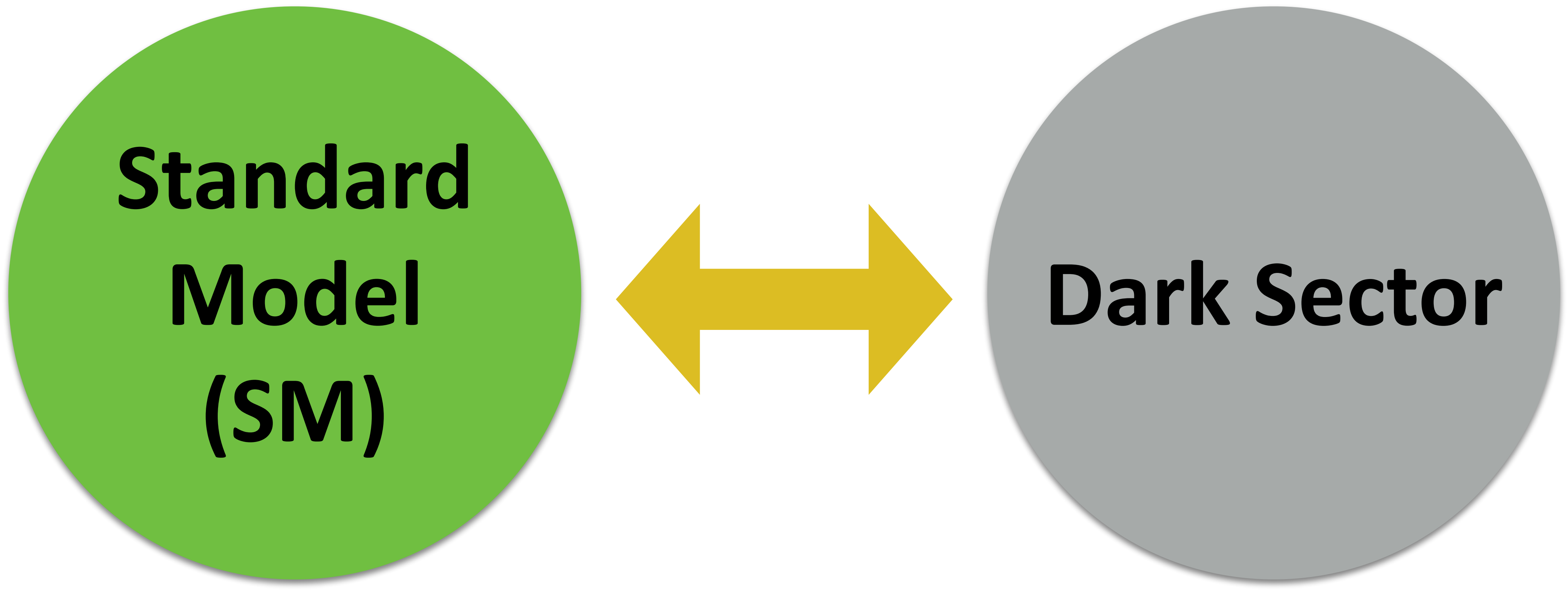
Millicharged particles



- There are multiple ways to get mili-charged particles
- A new U(1) in dark sector with massless dark-photon (A') and massive dark-fermion (ψ)
- A' and B kinetically mix

$$\mathcal{L}_{\text{dark sector}}$$
$$= -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not{\partial} + ie'\not{A}' + iM_{\text{mCP}}\right)\psi$$
$$-\frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

Millicharged particles



- There are multiple ways to get mili-charged particles
- A new U(1) in dark sector with massless dark-photon (A') and massive dark-fermion (ψ)
- A' and B kinetically mix
- Charge of ψ is proportional to mixing (κ)

$$\mathcal{L}_{\text{dark sector}}$$

$$= -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + iM_{\text{mCP}}\right)\psi$$

$$-\frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

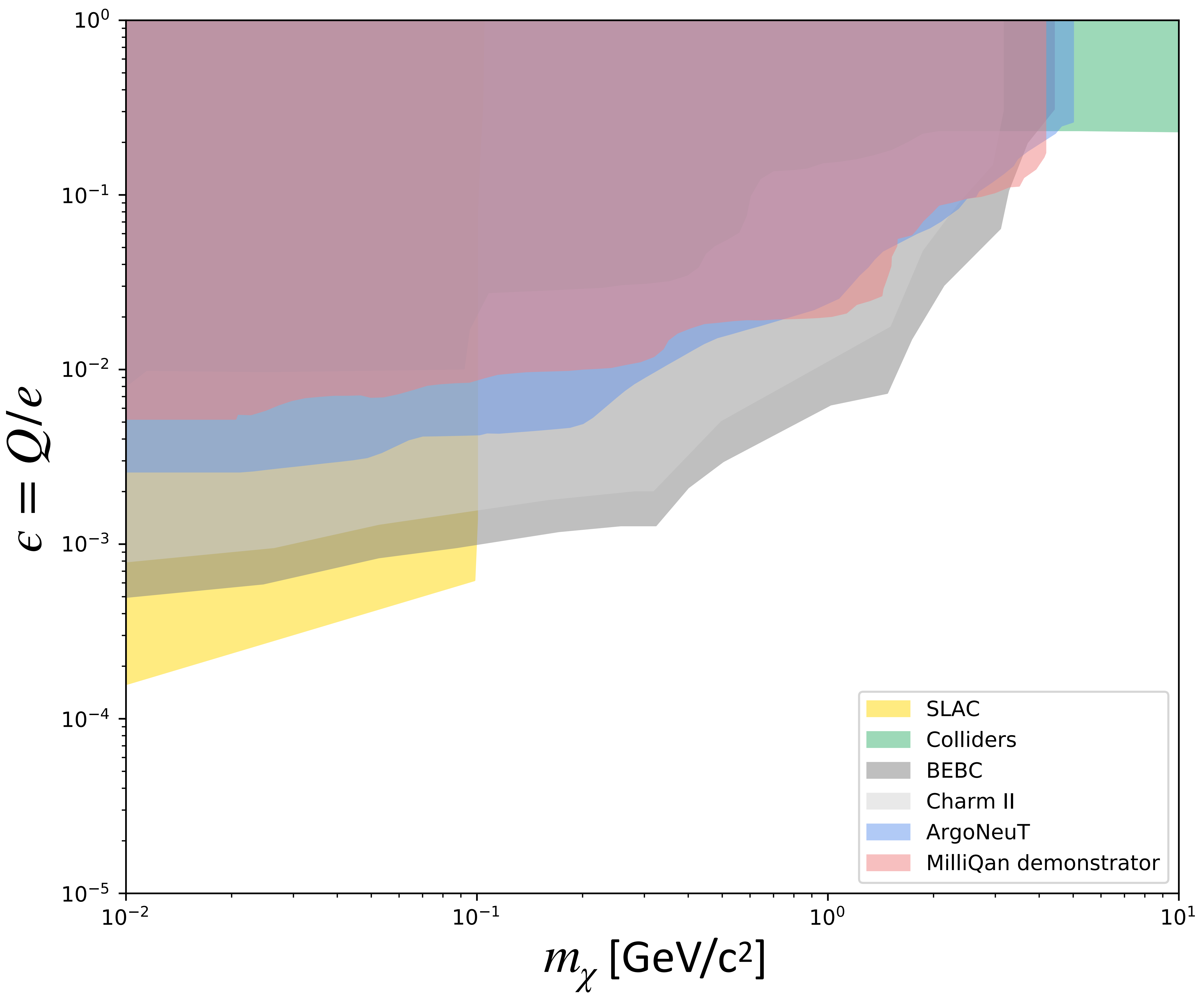
$$A'_\mu \to A'_\mu + \kappa B_\mu$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}$$

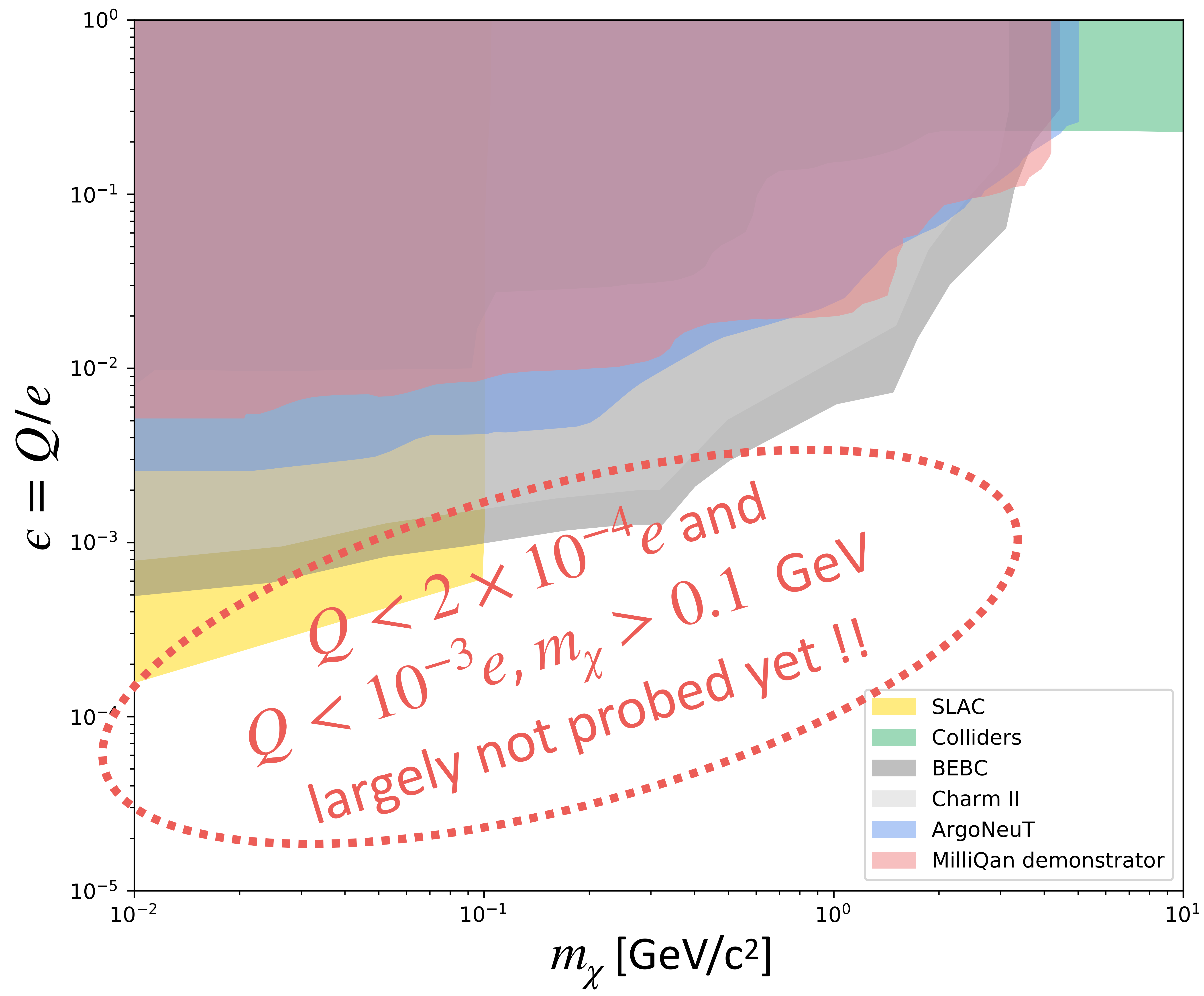
$$+ i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + i\kappa e' B\!\!\!/ + iM_{\text{mCP}}\right)\psi$$

coupling between ψ and SM photons with effective coupling (charge) $\kappa e'$ (typically $10^{-3} \sim 10^{-2}$)

Current reach



Current reach



New proposal at J-PARC: **SUBMET**

Proposal: Search for sub-millicharged particles at J-PARC

SUB-Millicharge ExperimenT (SUBMET)

Sungwoong Cho[1], Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Claudio Campagnari[2], Matthew Citron[2], David Stuart[2], Christopher S. Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], A. De Roeck[6], and Martin Gastal[6]

[1]*Korea University, Seoul, Korea*
[2]*University of California, Santa Barbara, California, USA*
[3]*The Ohio State University, Columbus, Ohio, USA*
[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*

Abstract

We propose a new experiment searching for sub-millicharged particles (χs) using 30 GeV proton fixed-target collisions at J-PARC. The detector is composed of two layers of stacked scintillator bars and PMTs and is proposed to be installed 280 m from the target. The main background is a random coincidence between two layers due to dark counts in PMTs, which can be reduced to a negligible level using the timing of the proton beam. With $N_{\mathrm{POT}} = 5\times10^{21}$ which corresponds to running the experiment for three years, the experiment provides sensitivity to χs with the charge down to $6\times10^{-5}e$ in $m_\chi < 0.2$ GeV/c^2 and $10^{-3}e$ in $m_\chi < 1.6$ GeV/c^2. This is the regime largely uncovered by the previous experiments.

- **SUB-M**illicharge **E**xperimen**T**
- Scintillator-based detector in proton fixed-target experiment at J-PARC
- Feasibility study has been published (JHEP 05 (2021) 031)

Letter of Intent: Search for sub-millicharged particles at J-PARC

Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Matthew Citron[2], David Stuart[2], Christopher S. Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], A. De Roeck[6], and Martin Gastal[6]

[1]*Korea University, Seoul, Korea*
[2]*University of California, Santa Barbara, California, USA*
[3]*The Ohio State University, Columbus, Ohio, USA*
[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*

Abstract

We propose a new experiment sensitive to the detection of millicharged particles produced at the 30 GeV proton fixed-target collisions at J-PARC. The potential site for the experiment is B2 of the Neutrino Monitor building, 280 m away from the target. With $N_{\mathrm{POT}} = 10^{22}$, the experiment can provide sensitivity to particles with electric charge $3\times10^{-4}\,e$ for mass less than 0.2 GeV/c^2 and $1.5\times10^{-3}\,e$ for mass less than 1.6 GeV/c^2. This brings a substantial extension to the current constraints on the charge and the mass of such particles.

JHEP

Published for SISSA by Springer

Received: *February 24, 2021*
Revised: *March 17, 2021*
Accepted: *April 1, 2021*
Published: *May 5, 2021*

Search for sub-millicharged particles at J-PARC

Jeong Hwa Kim, In Sung Hwang and Jae Hyeok Yoo[1]

Korea University,
145 Anam-ro, Seongbuk-gu, Seoul, 02841, Korea
E-mail: jailbraker@korea.ac.kr, his5624@korea.ac.kr, jaehyeokyoo@korea.ac.kr

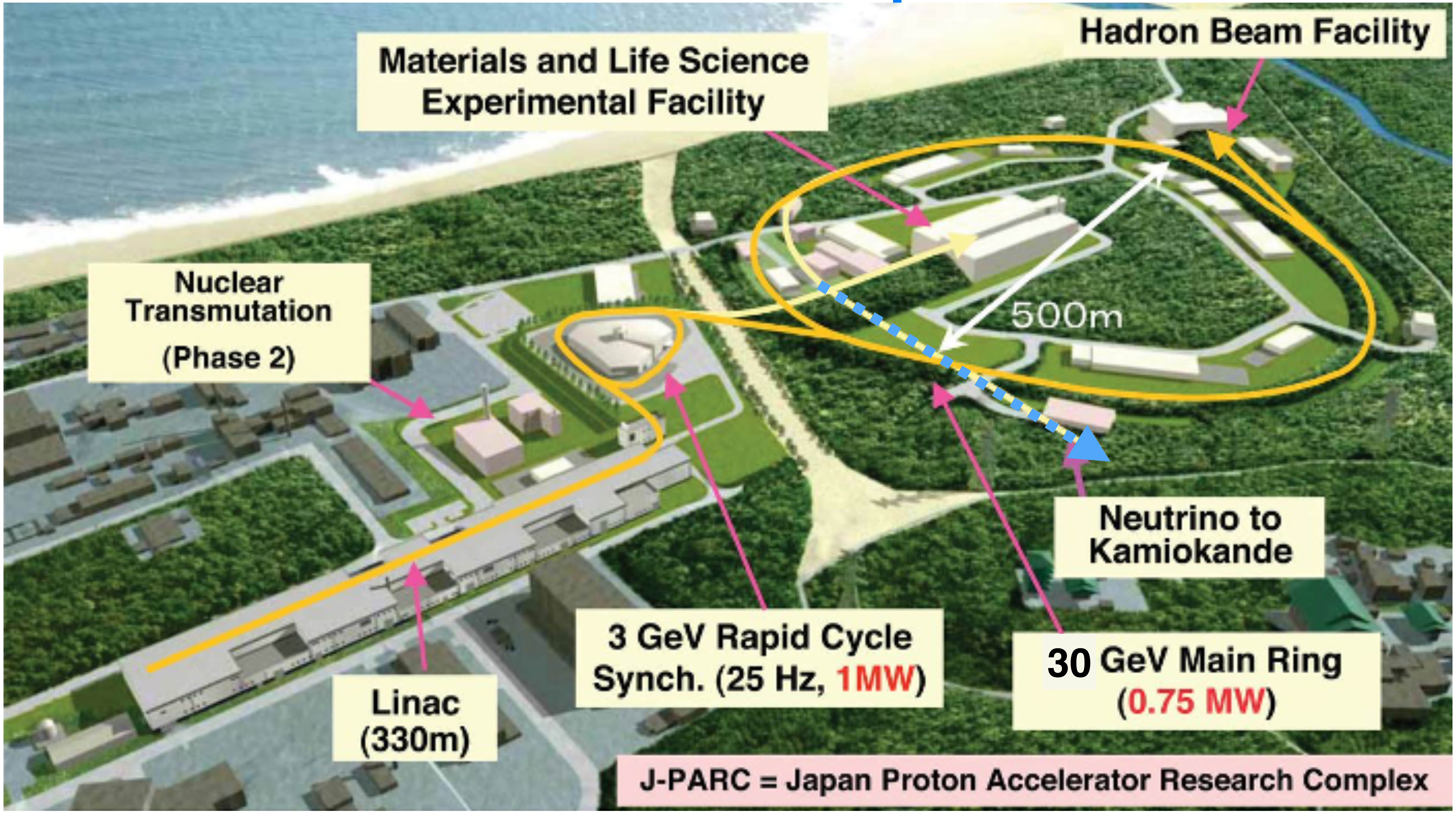
Abstract: We studied the feasibility of an experiment searching for sub-millicharged particles (χs) using 30 GeV proton fixed-target collisions at J-PARC. The detector is composed of two layers of stacked scintillator bars and PMTs and is proposed to be installed 280 m from the target. The main background is a random coincidence between two layers due to dark counts in PMTs, which can be reduced to a negligible level using the timing of the proton beam. With $N_{\mathrm{POT}} = 10^{22}$ which corresponds to running the experiment for three years, the experiment provides sensitivity to χs with the charge down to 5×10^{-5} in $m_\chi < 0.2$ GeV/c^2 and 8×10^{-4} in $m_\chi < 1.6$ GeV/c^2. This is the regime largely uncovered by previous experiments. We also explored a few detector designs to achieve optimal sensitivity to χs. The photoelectron yield is the main driver, but the sensitivity does not have a strong dependence on detector configuration in the sub-millicharge regime.

Keywords: Fixed target experiments, Dark matter

ArXiv ePrint: 2102.11493

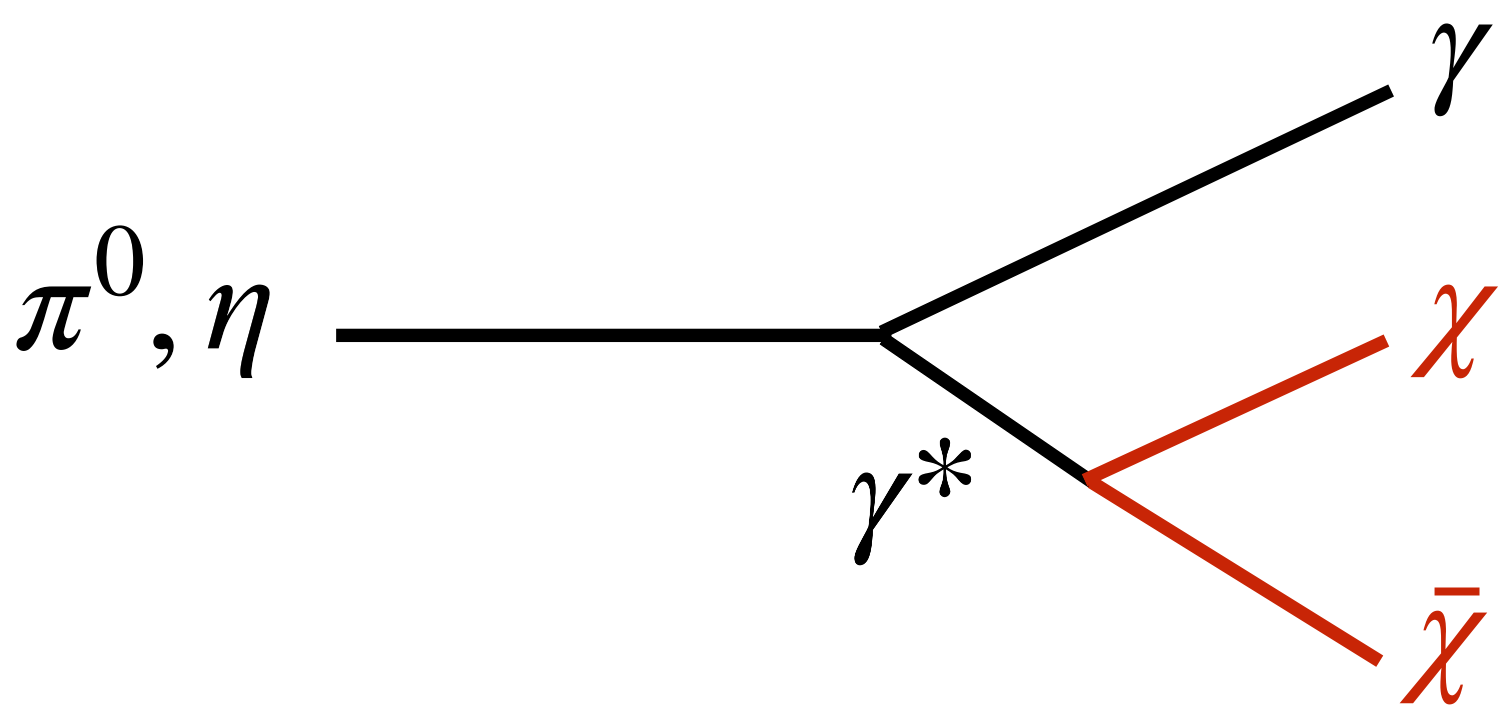
JHEP05(2021)031

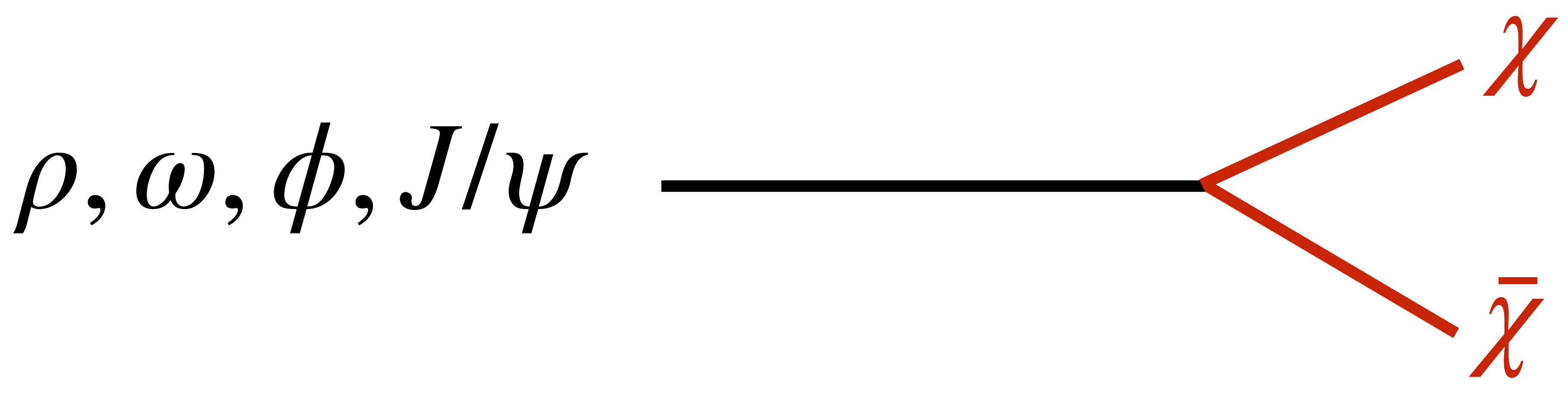
J-PARC complex



Production of mCPs

- χs can be produced from the decay of neutral mesons
  - π^0, η through a photon ($\pi^0, \eta \to \gamma\gamma^* \to \gamma\chi\bar{\chi}$)
  - $\rho, \omega, \phi,$ and J/ψ directly to $\chi\bar{\chi}$ ($\rho, \omega, \phi, J/\psi \to \gamma^* \to \chi\bar{\chi}$)





- In both cases, m_χ up to $m_{meson}/2$ is allowed

Production of mCPs

- The number of χs produced at the proton-target collisions is proportional to

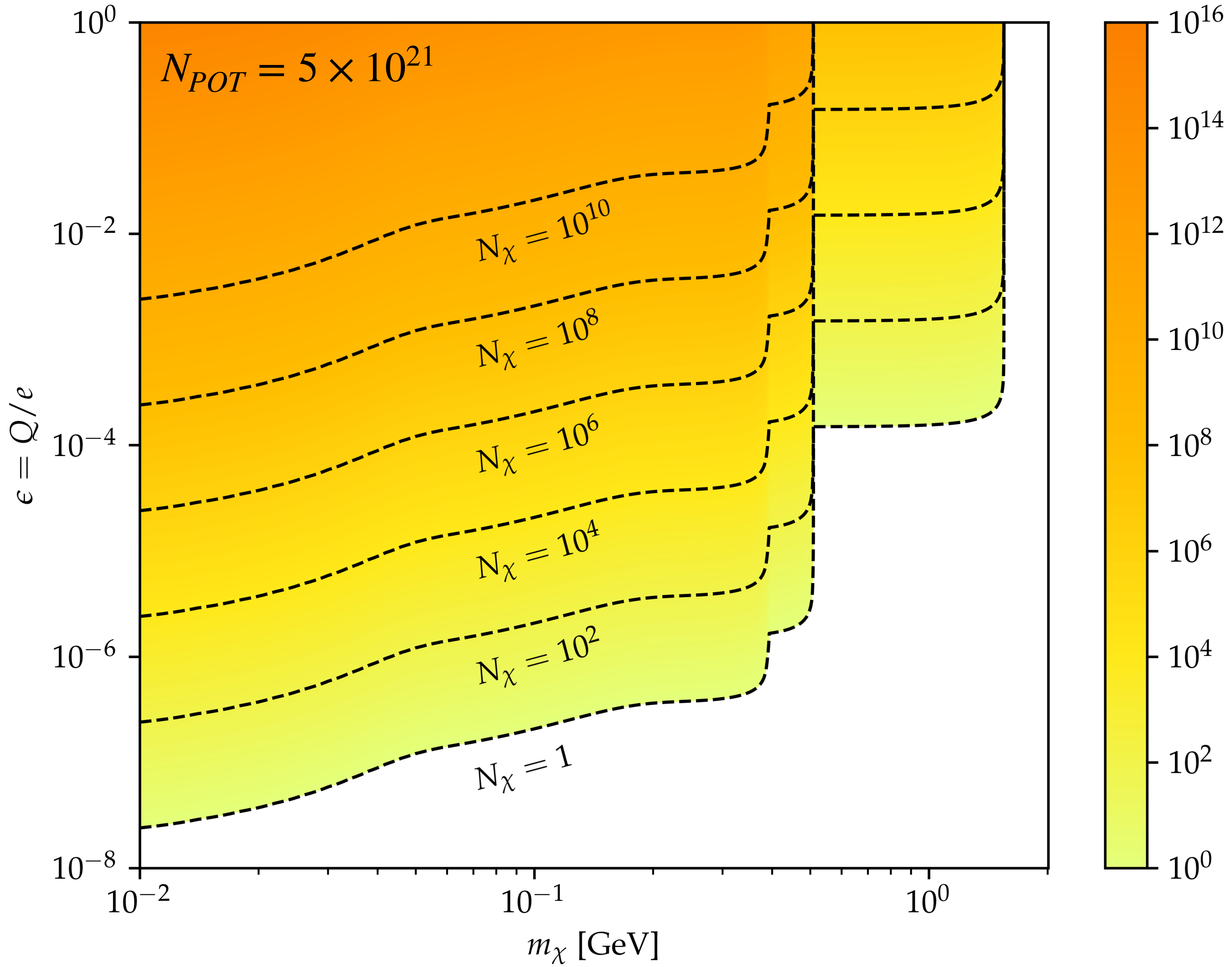
$$c_{meson}\epsilon^2 N_{POT} \times f\left(\frac{m_\chi^2}{m_{meson}^2}\right)$$

  - c_{meson}: number of mesons produced per proton-on-target (POT)
  - ϵ: Q/e where Q is the charge of χ and e is the electron charge
  - N_{POT}: total number of POT
  - f: phase space related integral that depends on m_χ and m_{meson}

- The values of c_{meson} for each meson are estimated from Pythia simulation

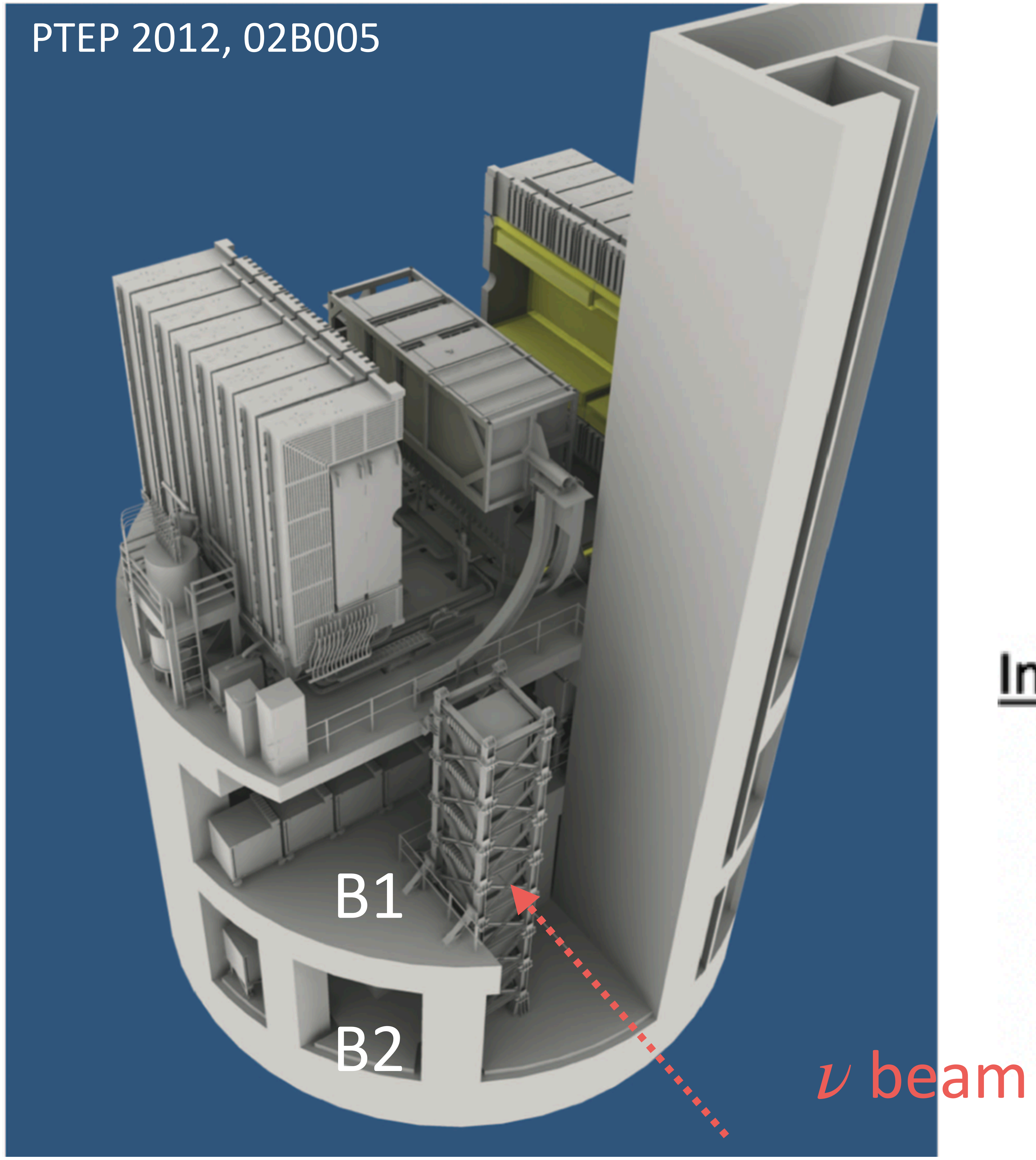
- Validated the simulation by comparison with measurements (flux of muons passing through the beam dump [*PTEP* 2015 (2015) 5, 053C01], production rate of J/ψ [*PLB* 638 407-414 (2006)])

Production of mCPs

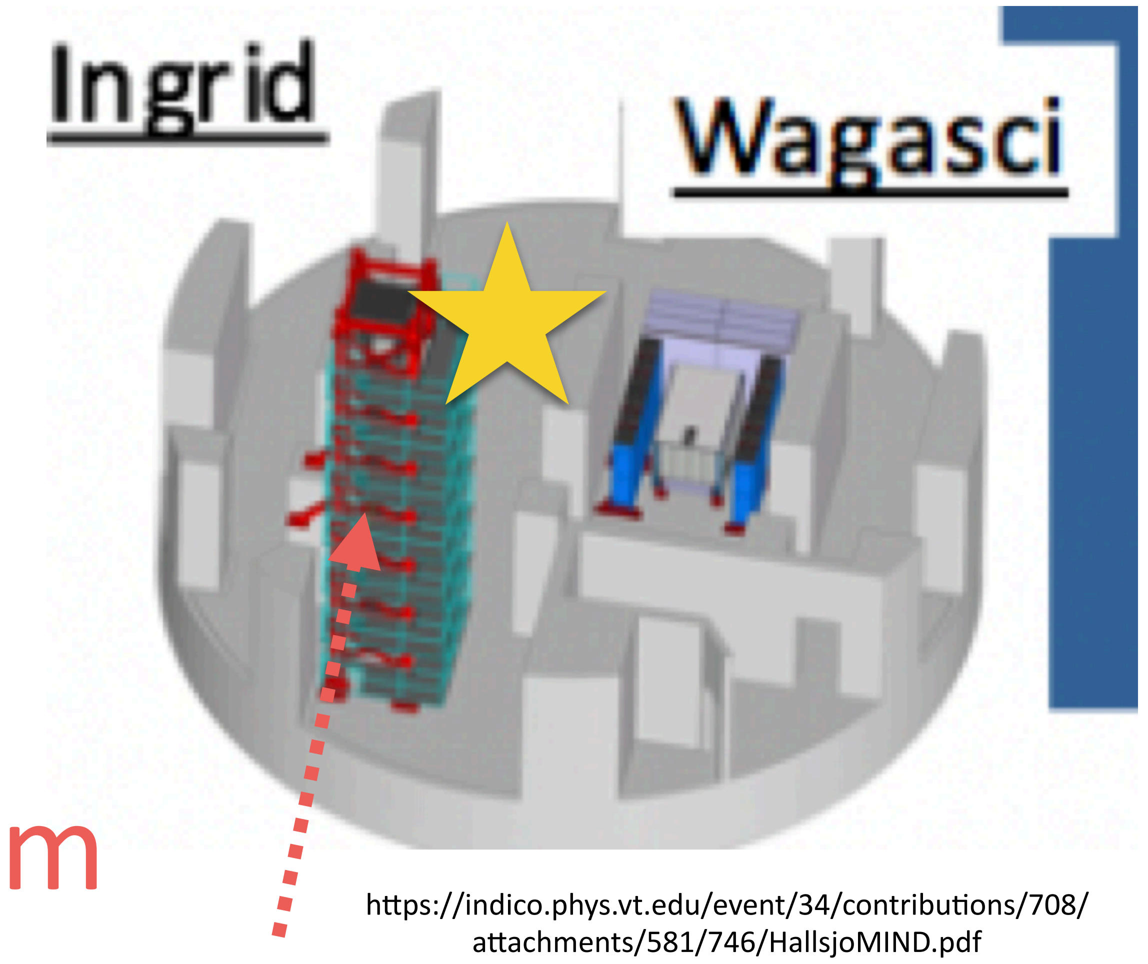


- Expected number of χs that reach 0.5×0.5 m² detector area (N_χ) in $N_{POT} = 5 \times 10^{21}$
- Expect $\sim 10^6$ χs where the exclusion limit is placed

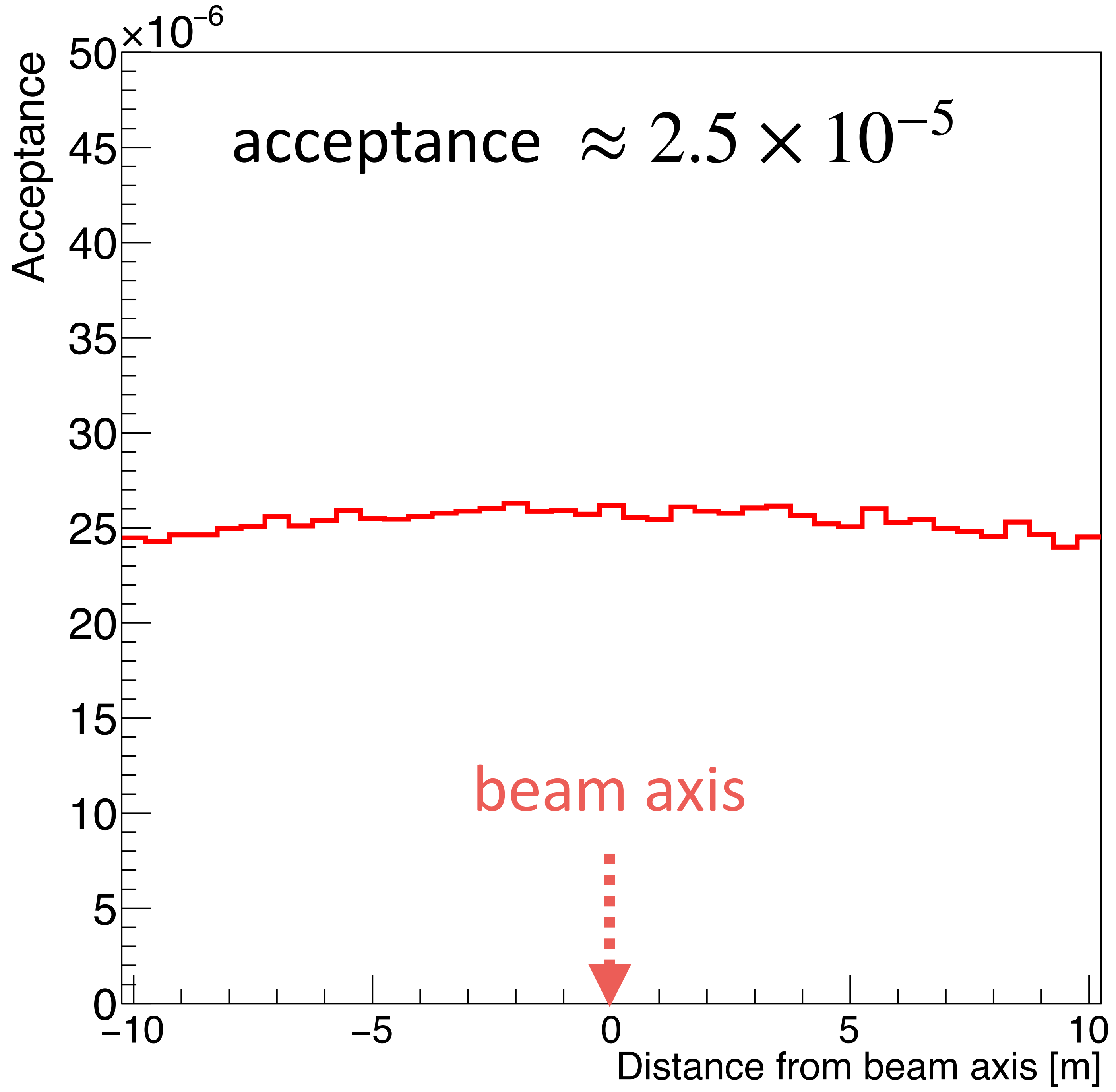
Potential experimental site



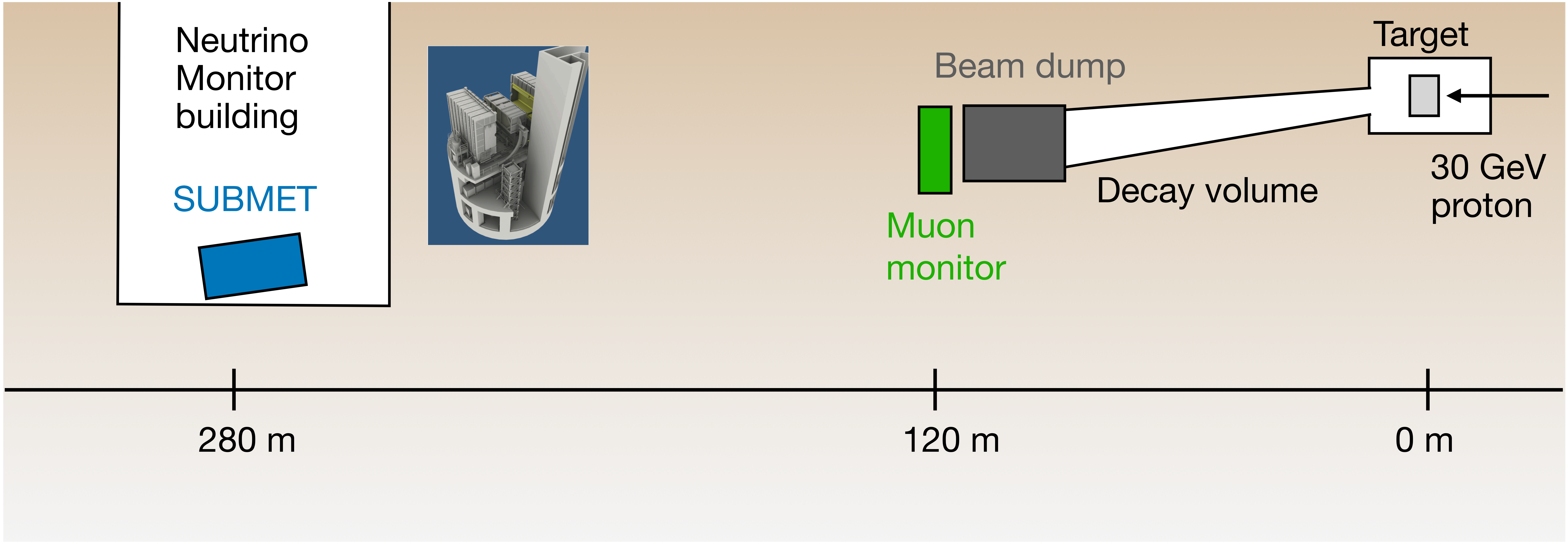
- Potential experimental site is on B2 of Neutrino Monitor building
  - Behind the V-INGRID (★) and a few meters from the beam axis
- Negligible difference in flux of χs from the beam axis



https://indico.phys.vt.edu/event/34/contributions/708/attachments/581/746/HallsjoMIND.pdf

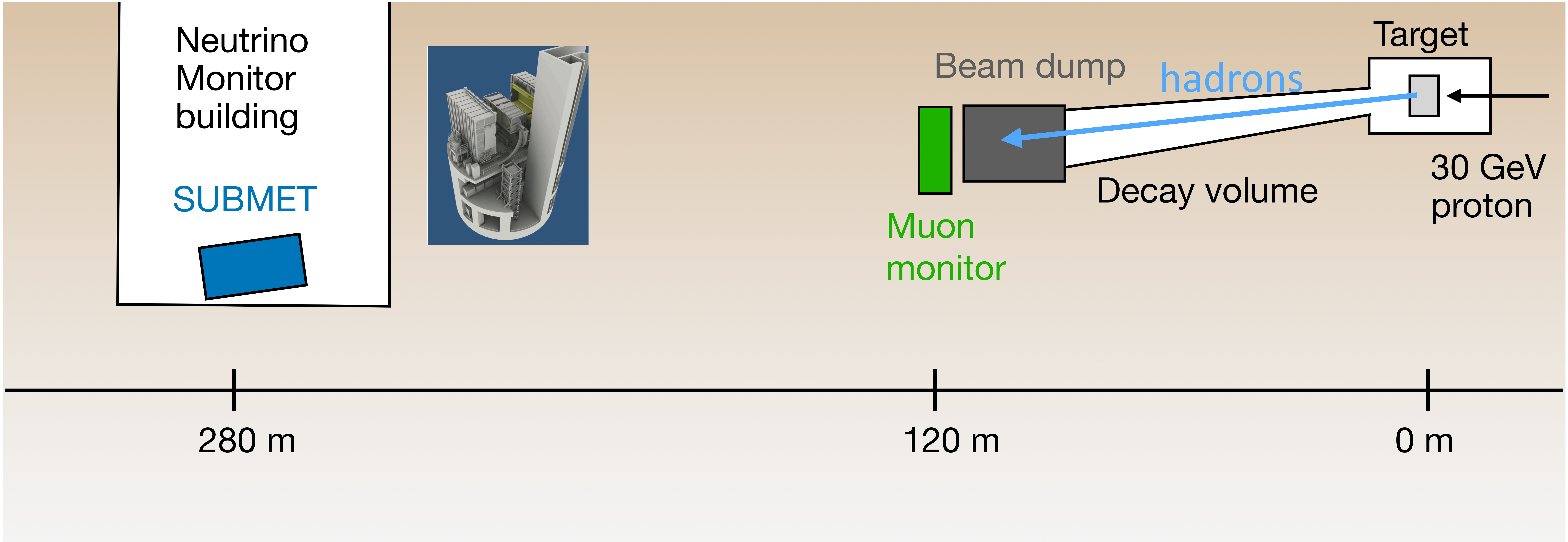


Basic idea of mCP detection



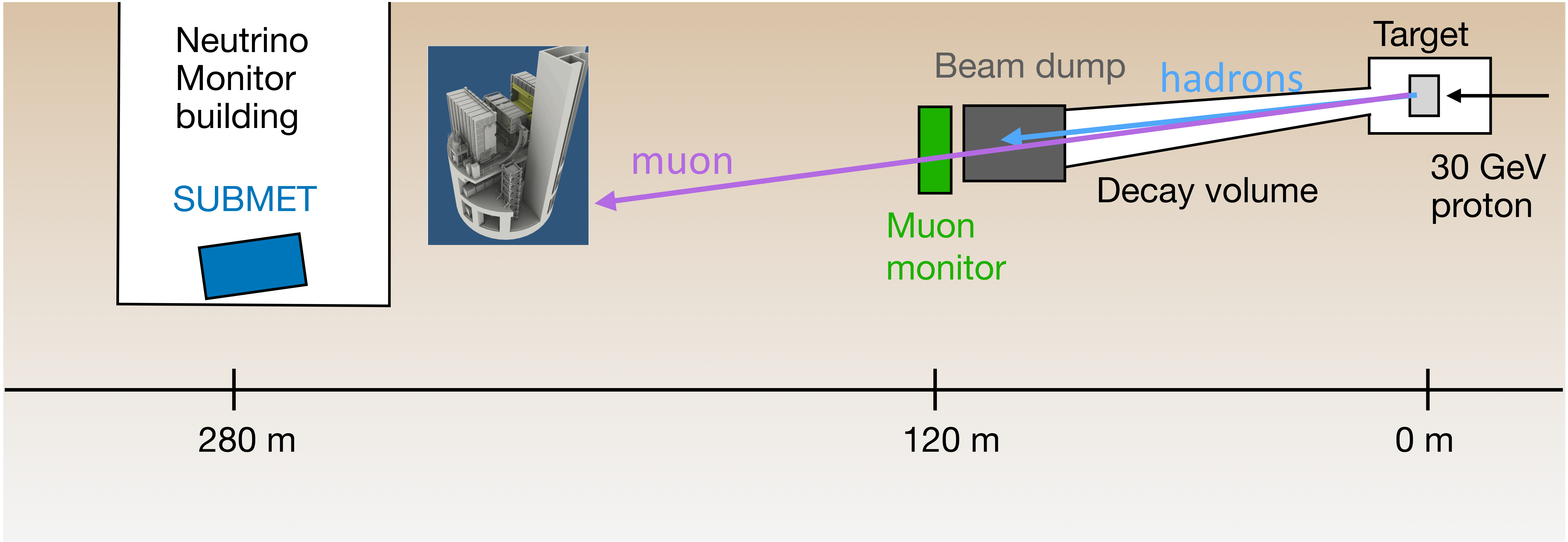
Protons hit the target and produce hadrons

Basic idea of mCP detection



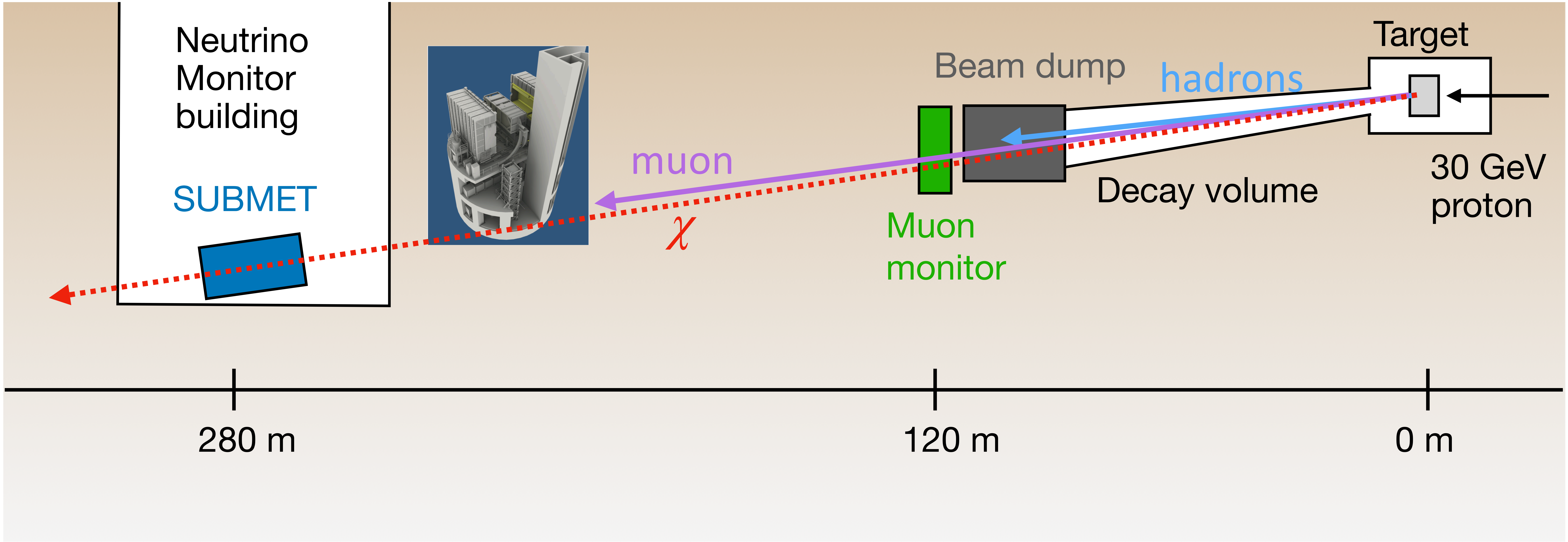
Hadrons are stopped in beam dump

Basic idea of mCP detection



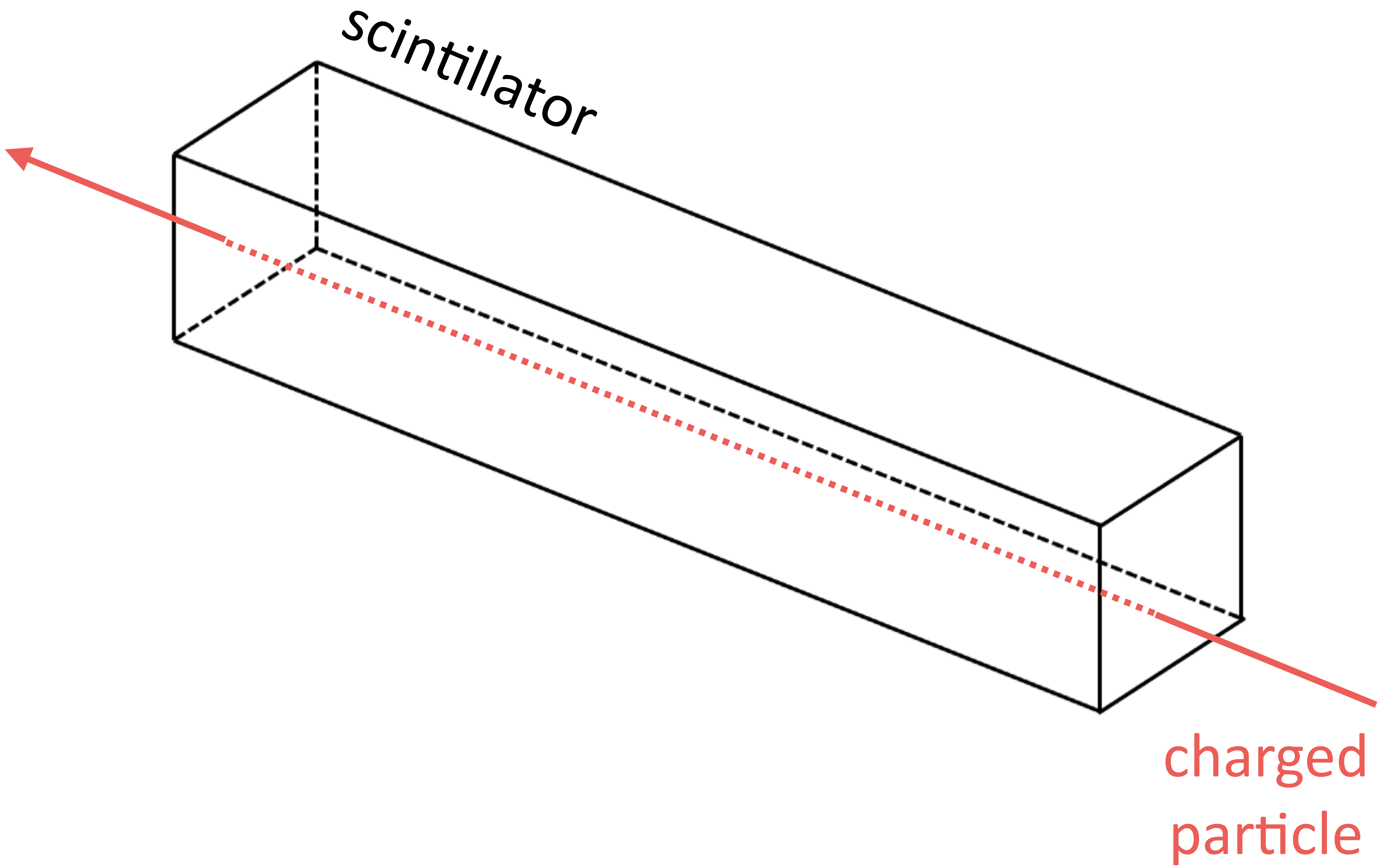
Muons pass the beam dump, but lose energy in sand (5 MeV/cm)
before reaching the Neutrino Monitor building

Basic idea of mCP detection



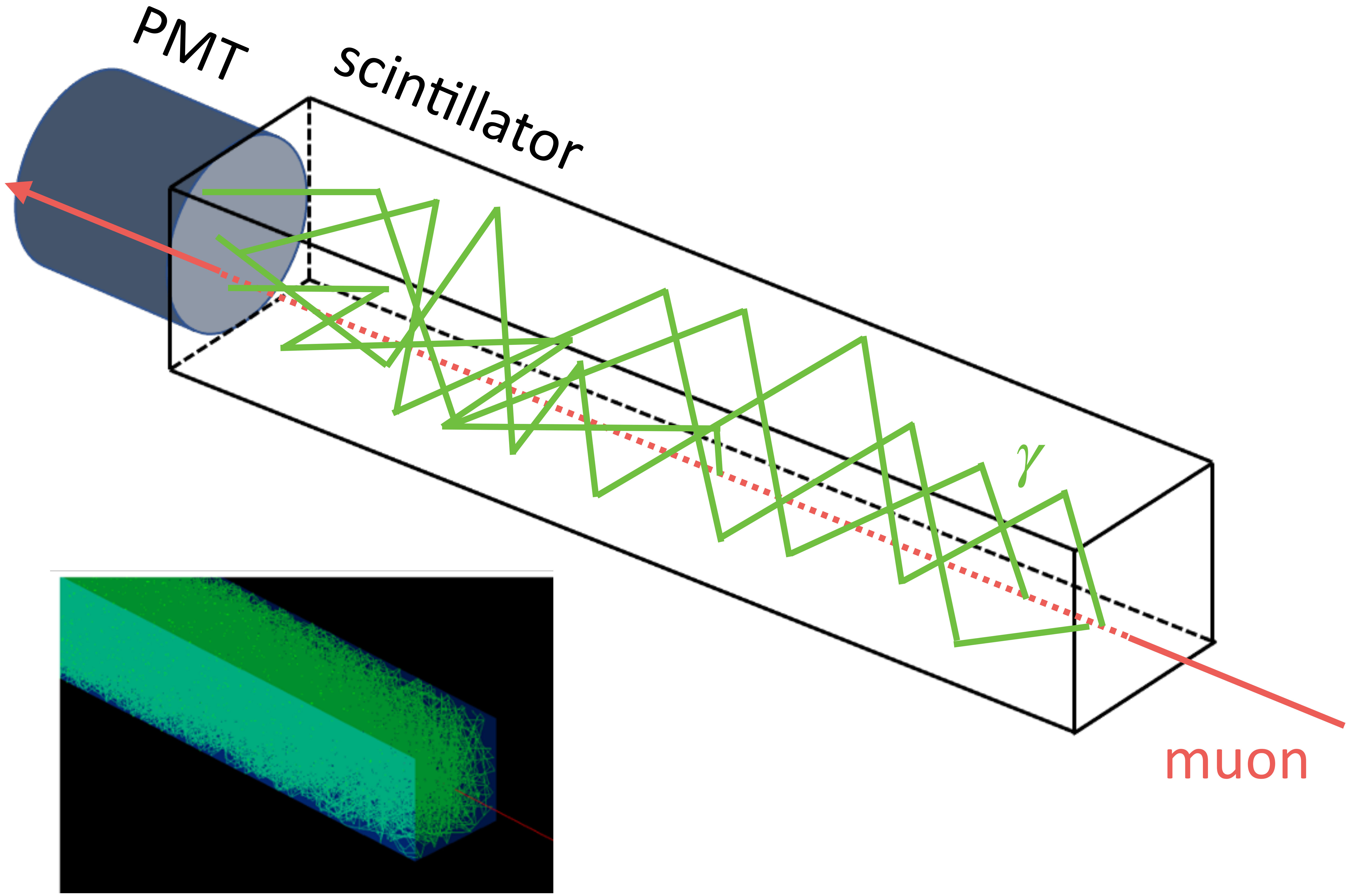
Only mCPs (and neutrinos) reach the detector
(energy loss for mCPs with $Q = 10^{-3}e$ is <0.1 MeV)

Detection principle



- When a charged particle goes through a scintillator, photons are produced

Detection principle

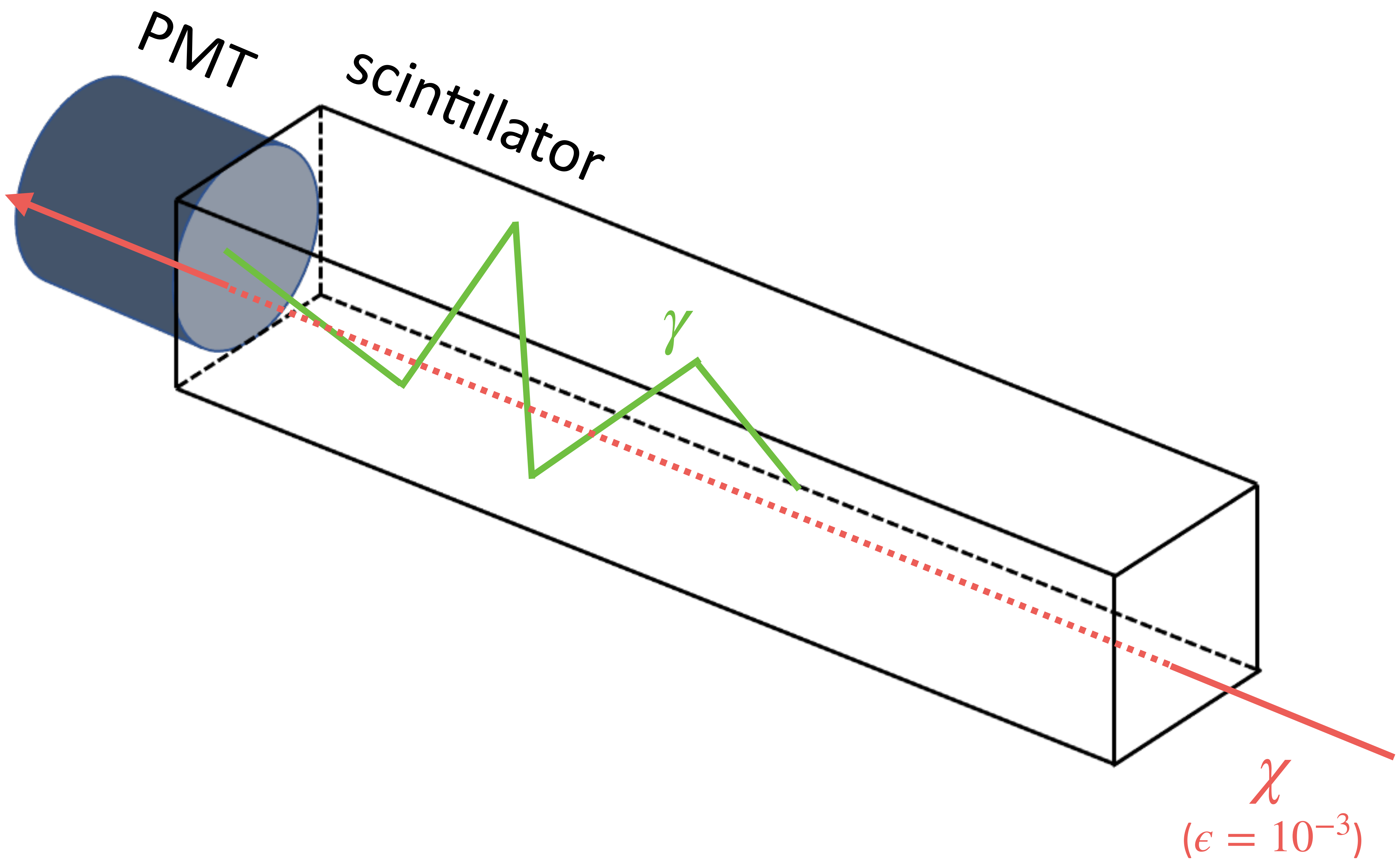


Geant4 simulation

- When a charged particle goes through a scintillator, photons are produced

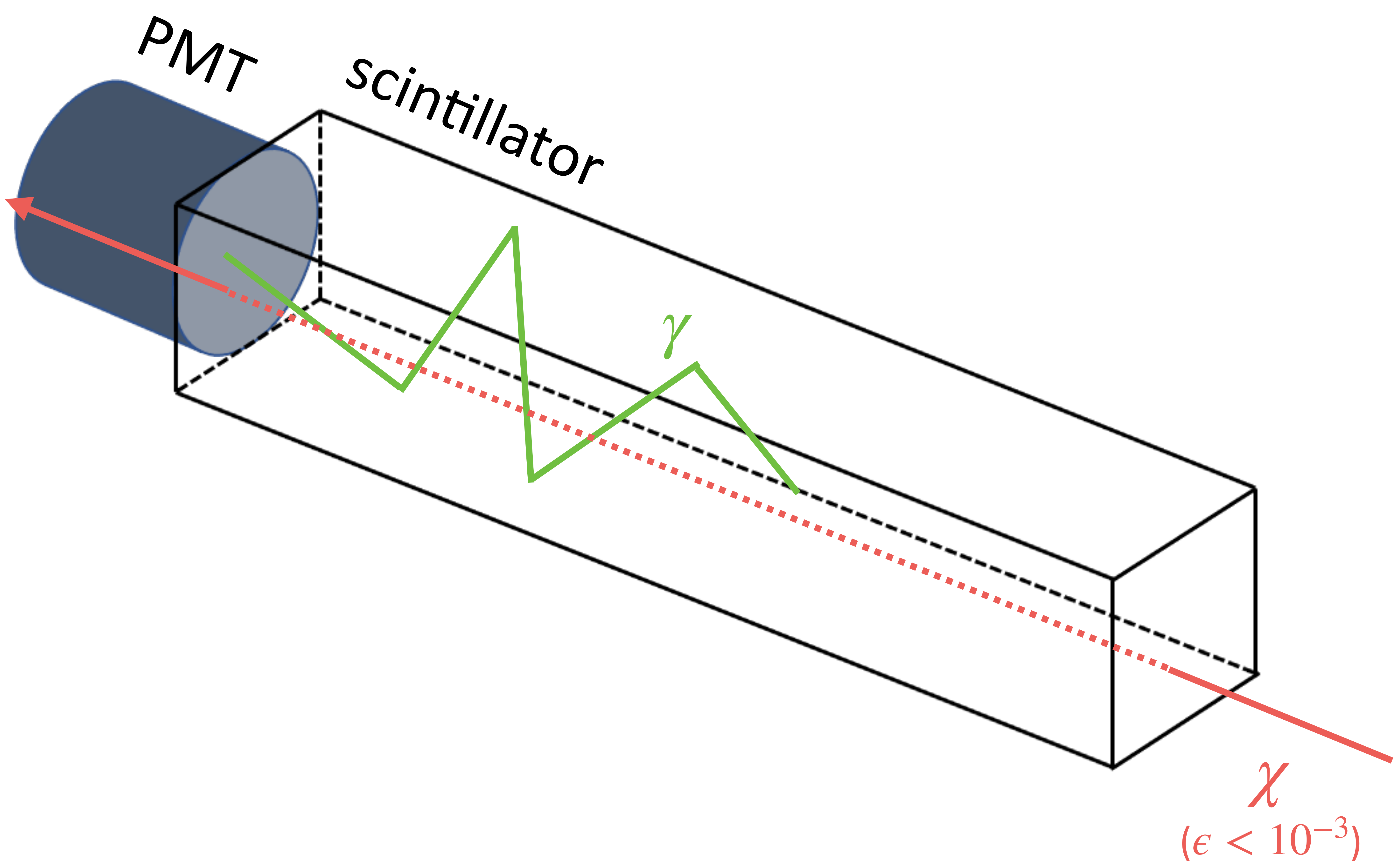
- For a muon, the number of photons N_γ is $O(10^6)$

Detection principle



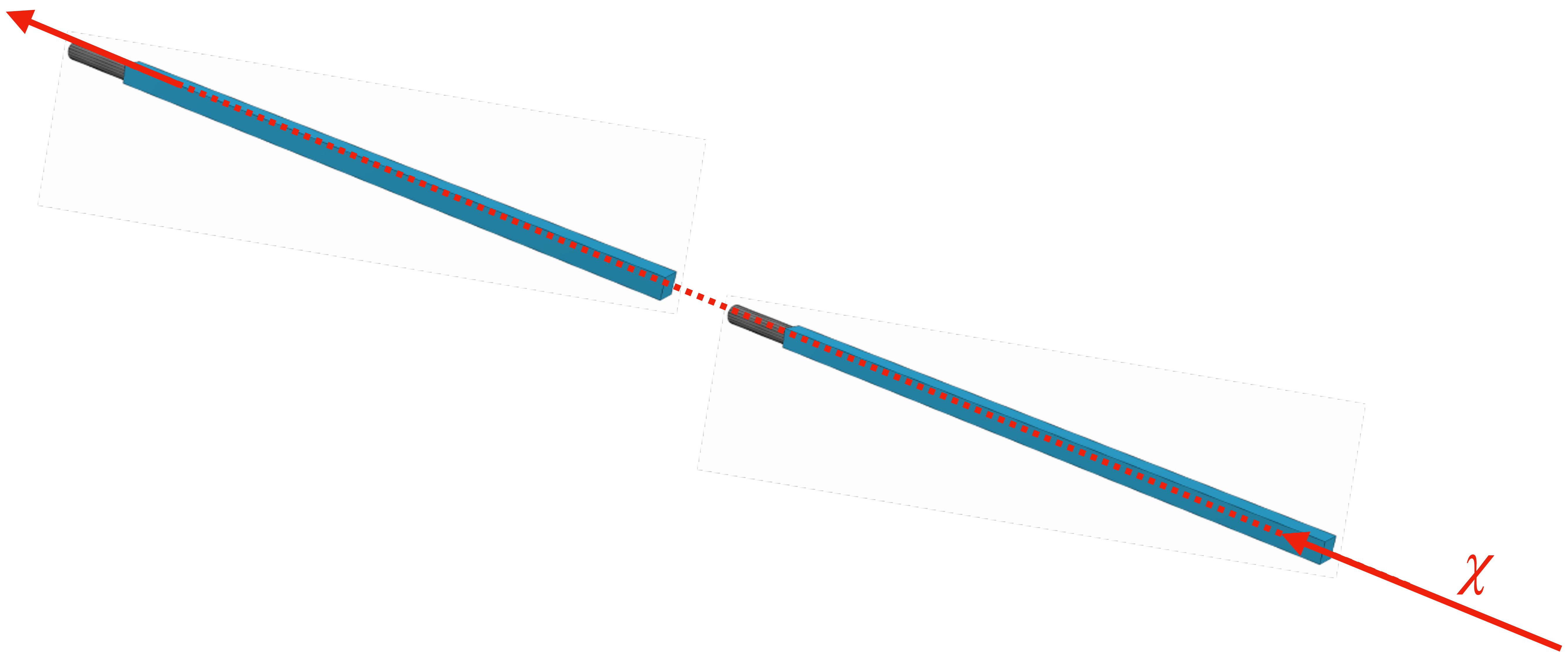
- When a charged particle goes through a scintillator, photons are produced
- For a muon, the number of photons N_γ is $O(10^6)$
- The produced photons are detected by a PMT
- N_γ is proportional to ϵ^2
  - For $\epsilon = 10^{-3}, N_\gamma = O(1)$

Detection principle



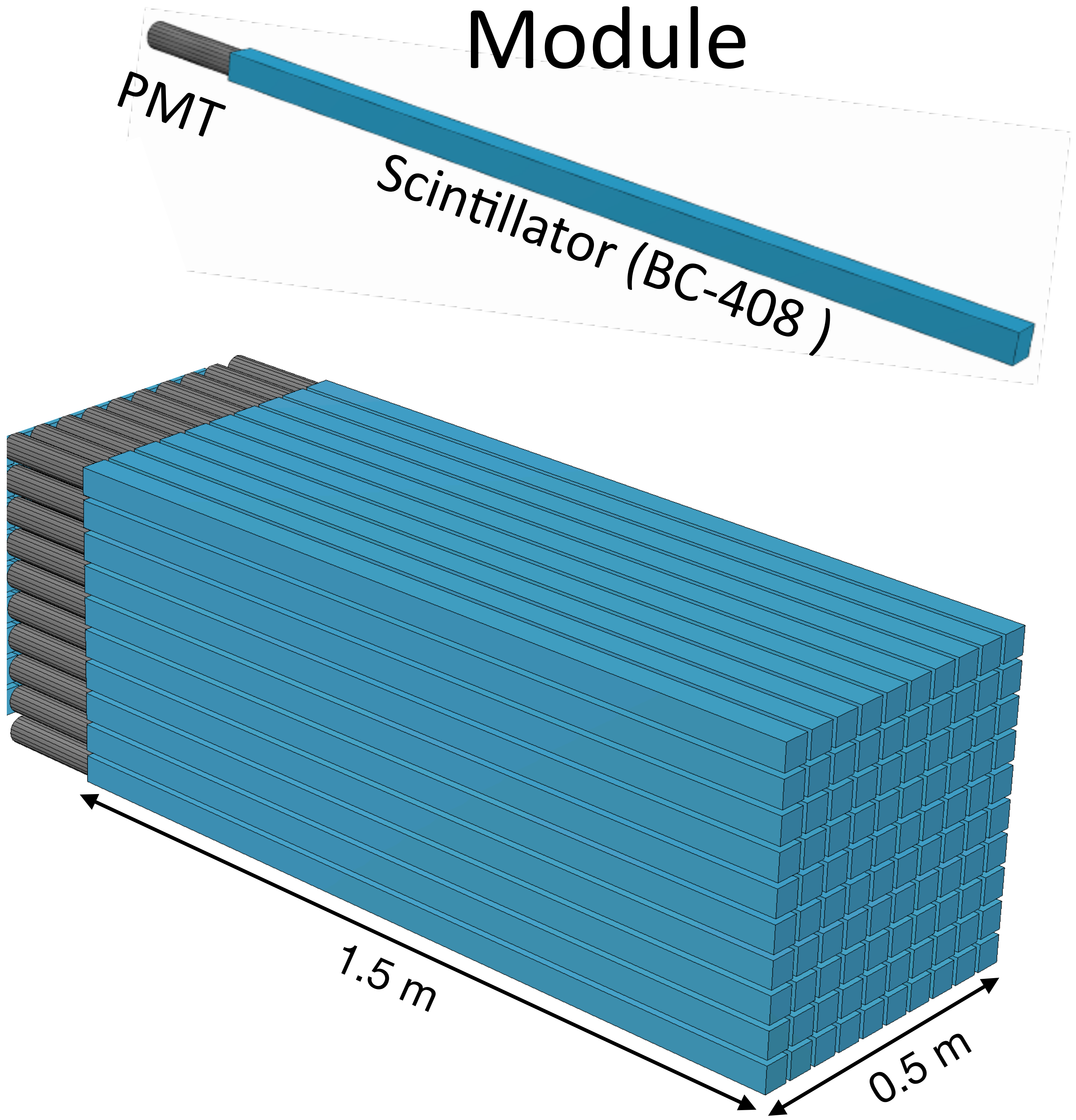
- For $\epsilon < 10^{-3},\ N_\gamma < O(1)$
- N_γ is the mean of Poisson, so there is still a probability for photons to be produced (mostly single photon)
- For small charges ($\epsilon < 10^{-3}$), it becomes a matter of measuring single photoelectron

Detector concept



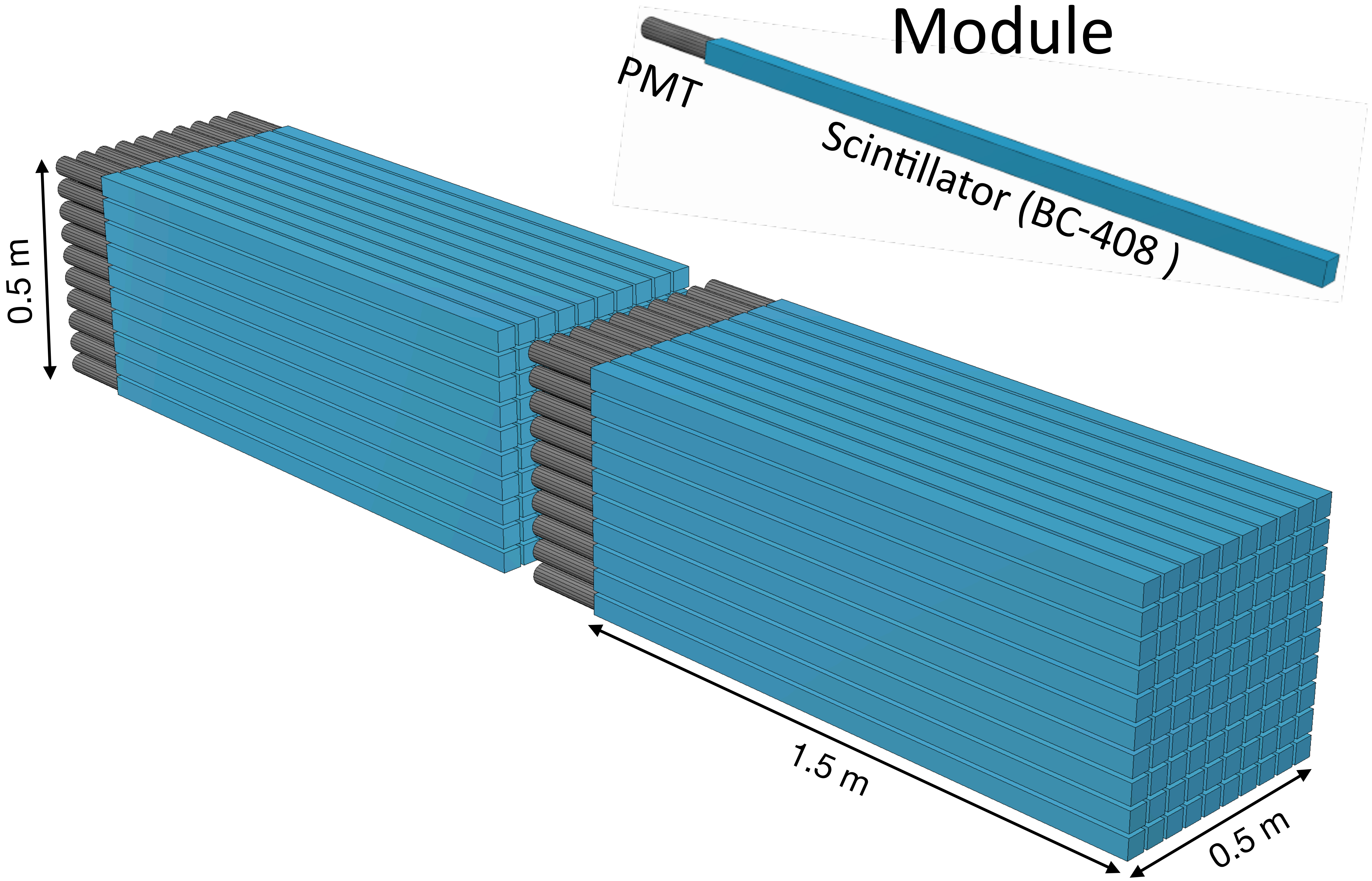
- Number of χs detected by n scintillators is $N_{signal} = N_\chi P^n$
  - N_χ is the number of χs that reach the detector
  - P is the detection probability per scintillator

Detector concept



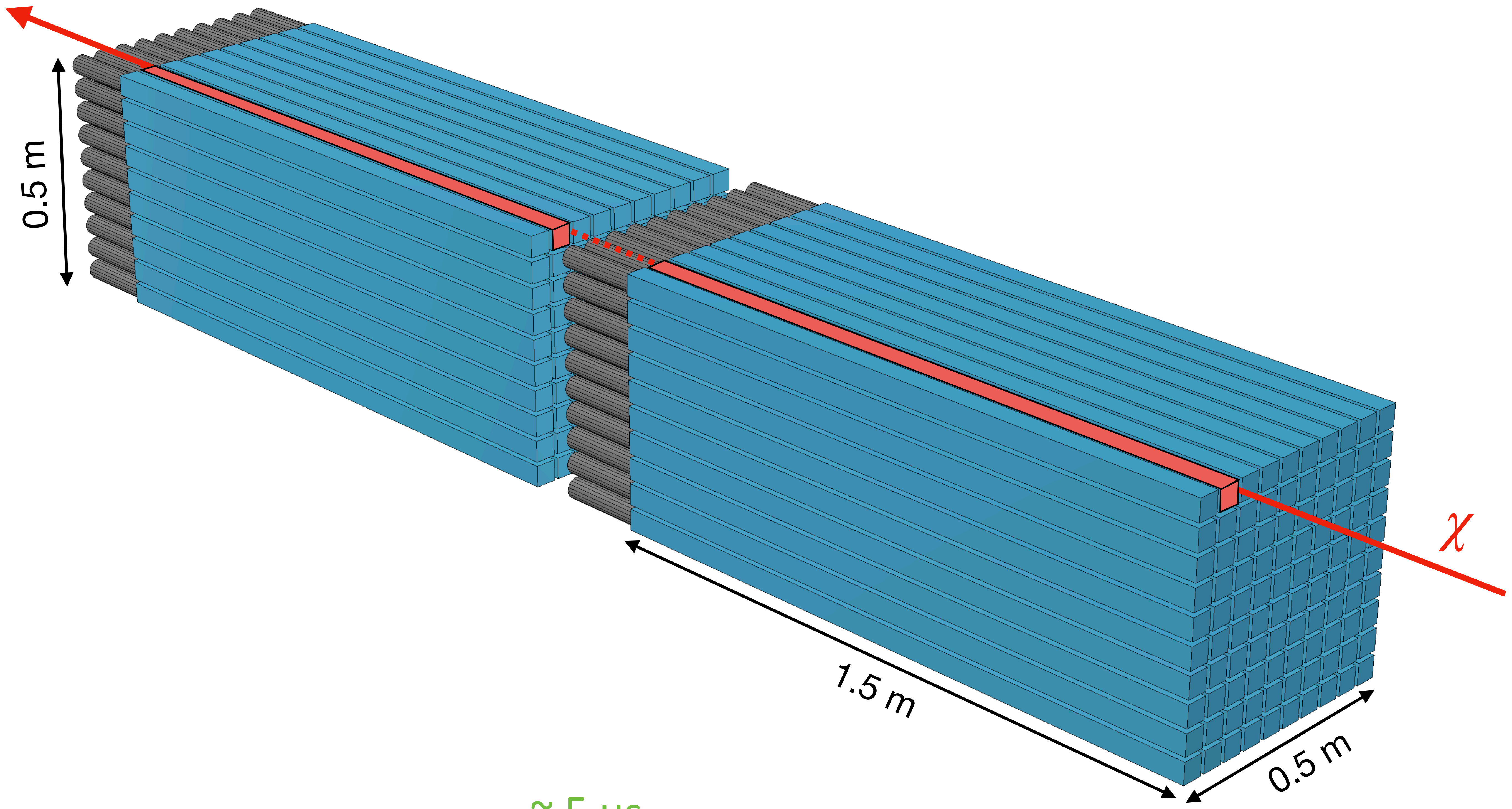
- Number of χs detected by n scintillators is $N_{signal} = N_\chi P^n$
  - N_χ is the number of χs that reach the detector
  - P is the detection probability per scintillator
- Stack of modules (10x10) to increase active volume
  - Module = scintillator (5x5x150 cm^3) + PMT
  - Detector area = 0.5 x 0.5 m^2 = 0.25 m^2

Detector concept

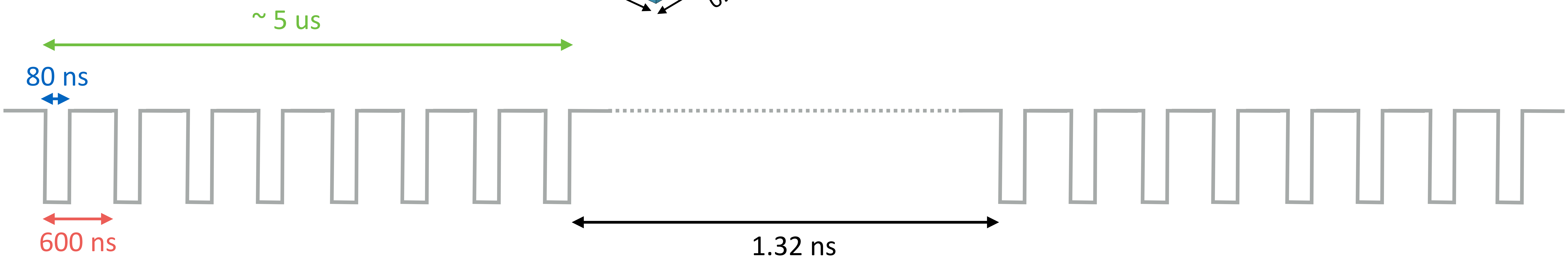


- Number of χs detected by n scintillators is $N_{signal} = N_\chi P^n$
  - N_χ is the number of χs that reach the detector
  - P is the detection probability per scintillator
- Stack of modules (10x10) to increase active volume
  - Module = scintillator (5x5x150 cm^3) + PMT
  - Detector area = 0.5 x 0.5 m^2 = 0.25 m^2
- Divide them to 2 layers to control backgrounds
  - More layers $\rightarrow$ easier to control backgrounds
  - Less layers $\rightarrow$ higher detection probability

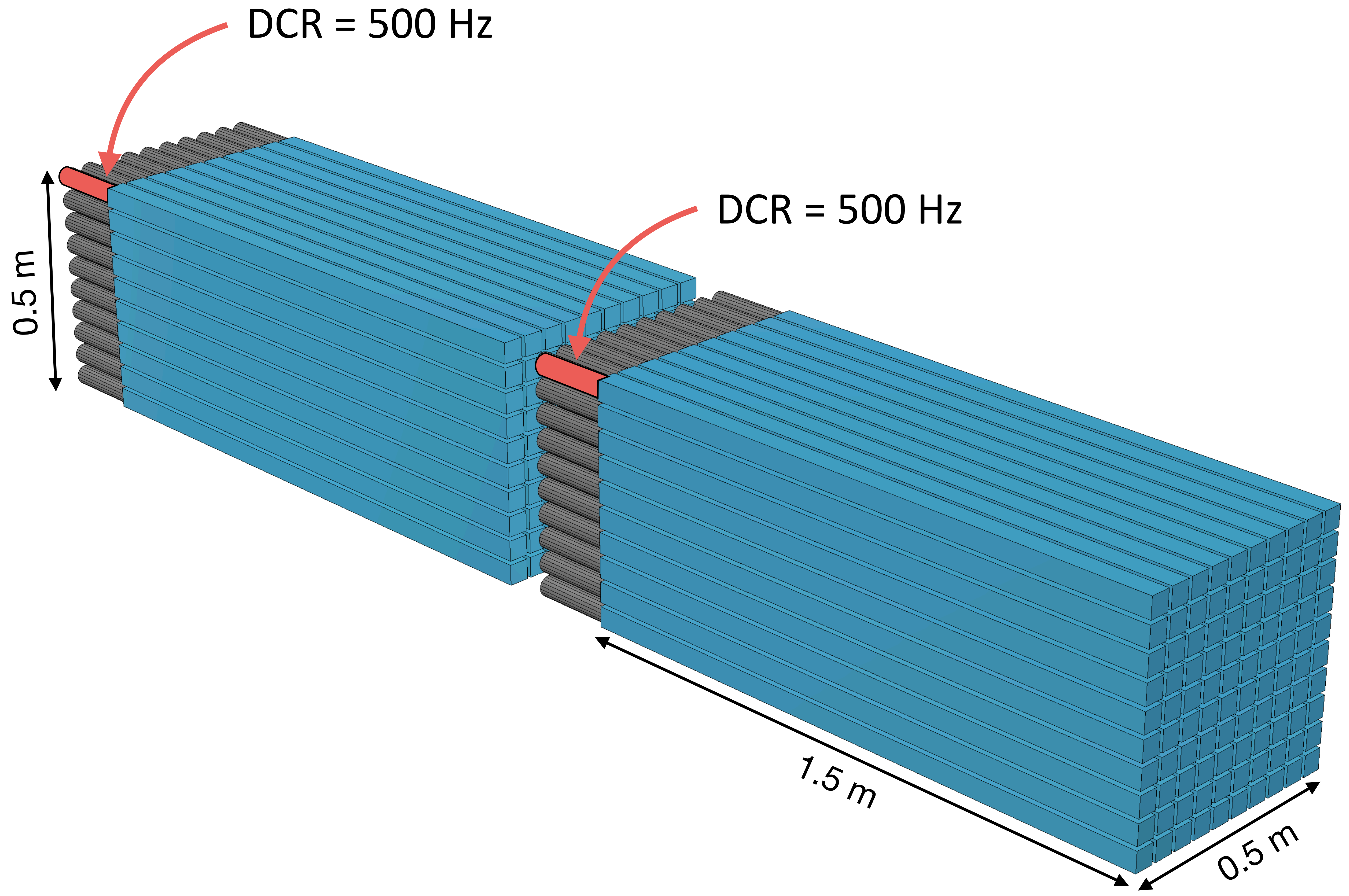
Detector concept



- Align the two layers such that a χ goes through them
- Require small time interval between hits ($\Delta t = 10$ ns) in the two layers and use the timing/structure of the proton beam ($O(10^{-6})$ reduction)
  - can reduce backgrounds significantly

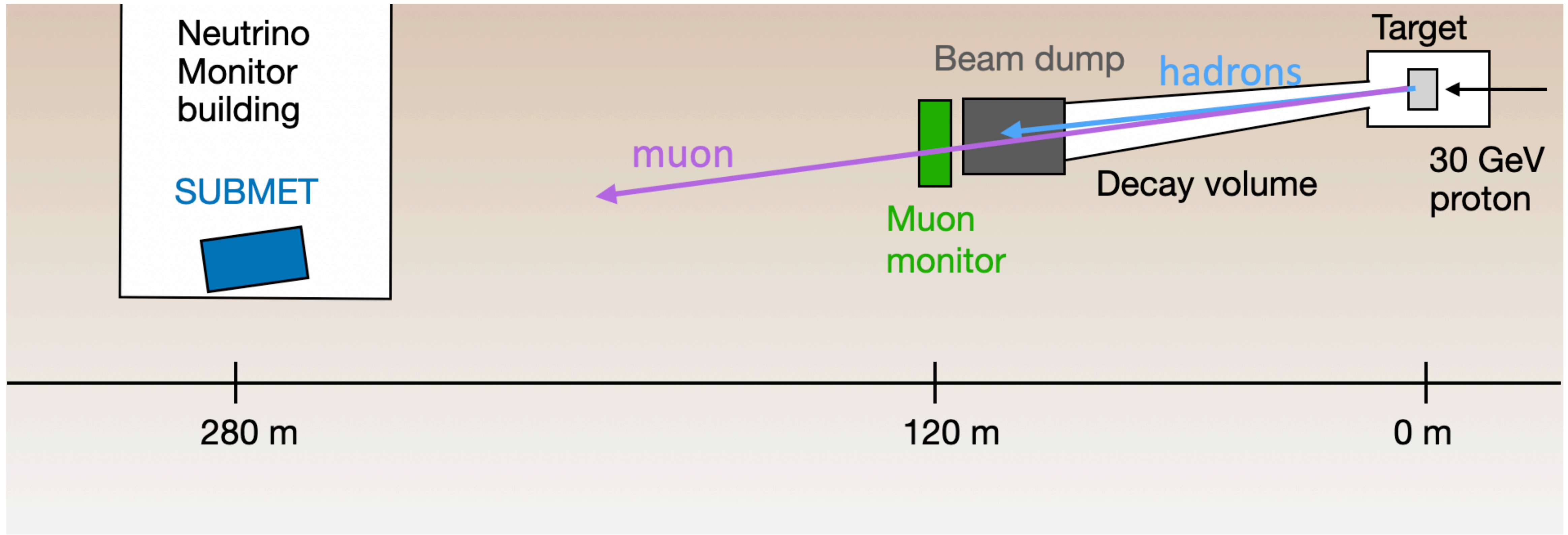


Backgrounds (detector)



- Random coincidence of PMT dark counts
- Random coincidence rate: $nN^n\tau^{n-1}$
  - n: number of layers
  - N: dark count rate per PMT
  - τ: coincidence window
- Using $N = 500$ Hz, $n = 2$, and $\tau = 10$ ns and reduction of $O(10^{-6})$ using beam timing, total coincidence rate is 15 per year
  - Can you reproduce this number?
- By cooling PMTs, this background can be reduced to a negligible level, e.g., <1 for $N = 100$ Hz

Backgrounds (beam-related)



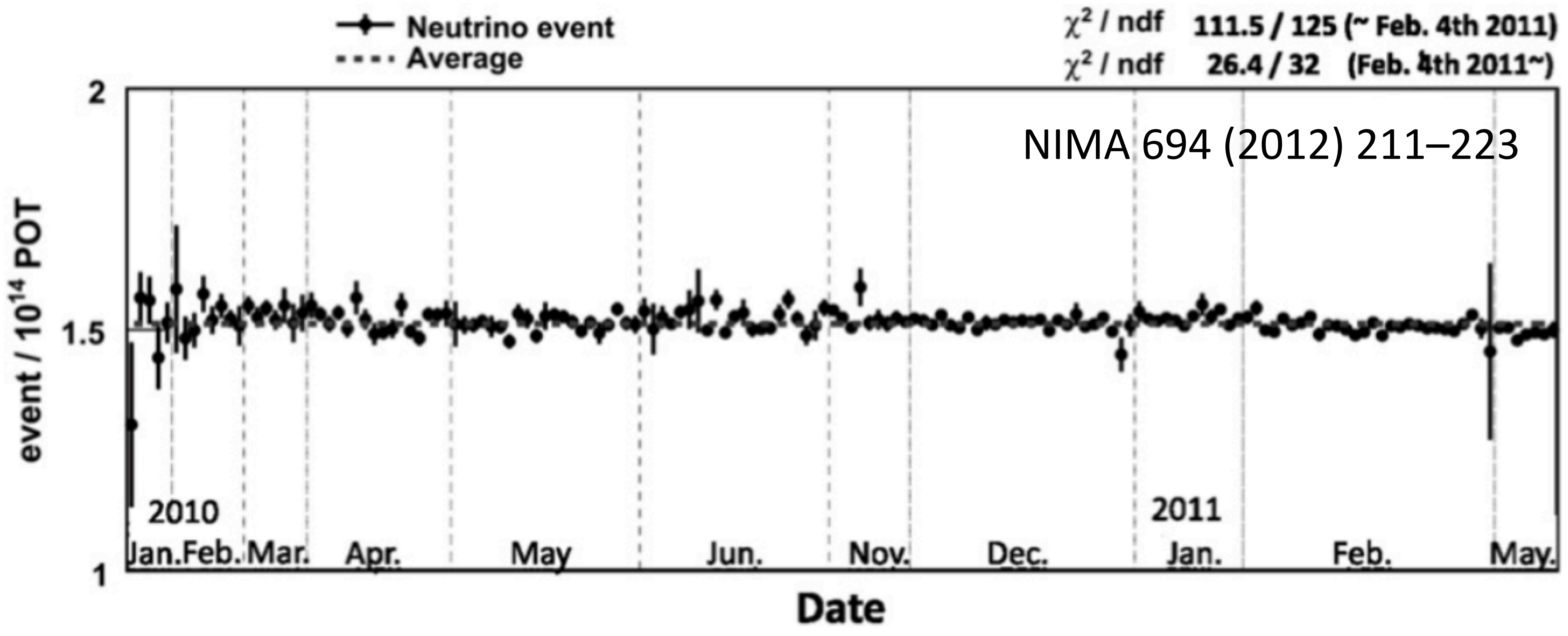
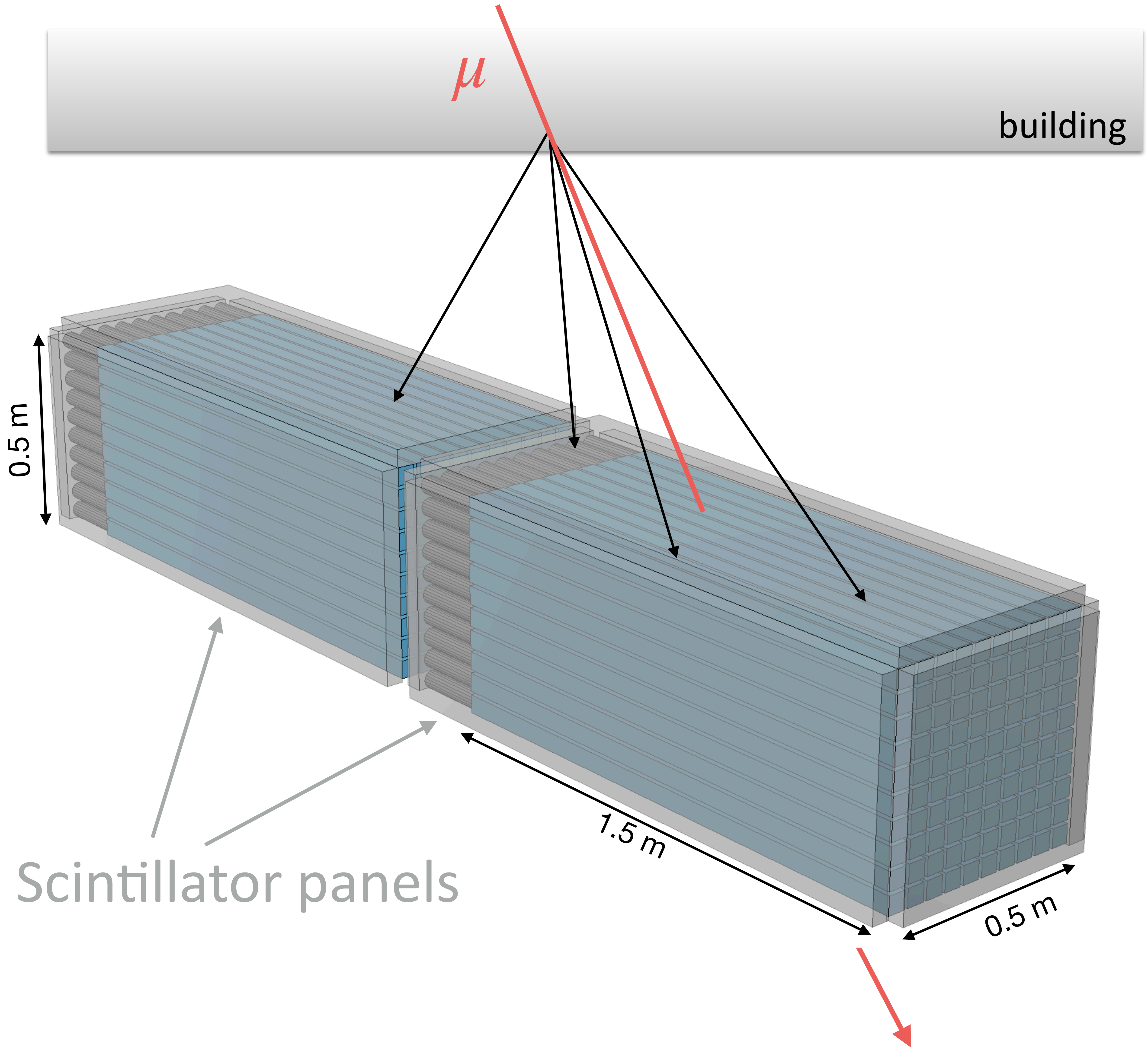


Fig. 24. Daily event rate of the neutrino events normalized by protons on target.

- Muons from hadron decays do not reach detector due to energy loss
- Neutrino interactions with scintillator
  - Refer to the measurements by INGRID: 8×10^7 for $N_{POT} = 5\times10^{21}$
  - Iron: denser material → upper bound
  - Considering volume difference (1/50) and requiring coincidence, the rate becomes negligible
- Muons from interactions between neutrinos and the material of the building can be identified/rejected by installing scintillator plates in front of the detector

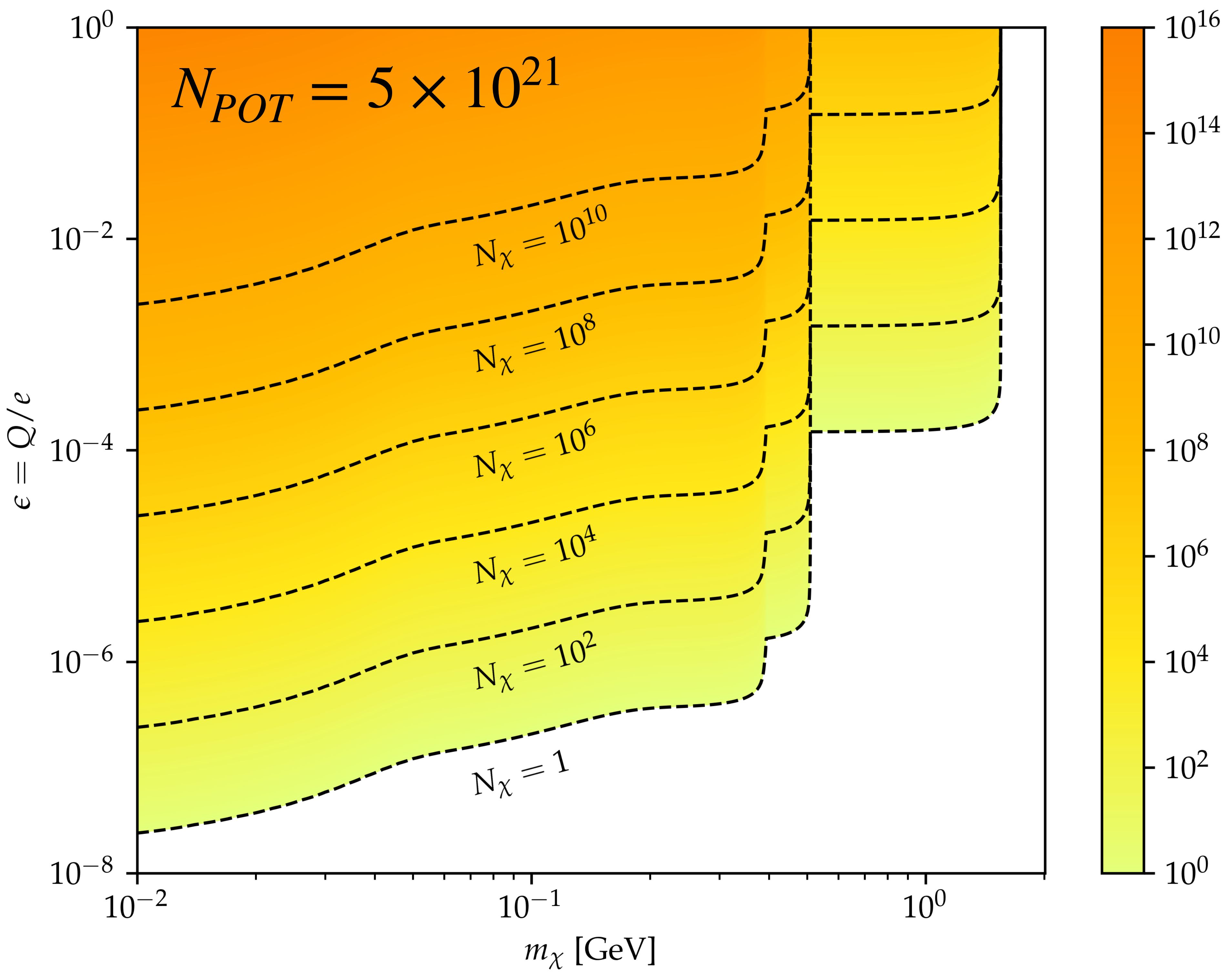
Backgrounds (cosmic muons)



- Shower produced by cosmic muons hitting the structure of the building
  - Shower particles can hit both layers at the same time
  - Typically large number of hits and larger energy deposits
- Can be rejected by scintillator panels covering top/sides or using the outermost bars
- Precise measurement should be performed *in situ*

Production → detection

Number of χs that reach the detector (N_χ)



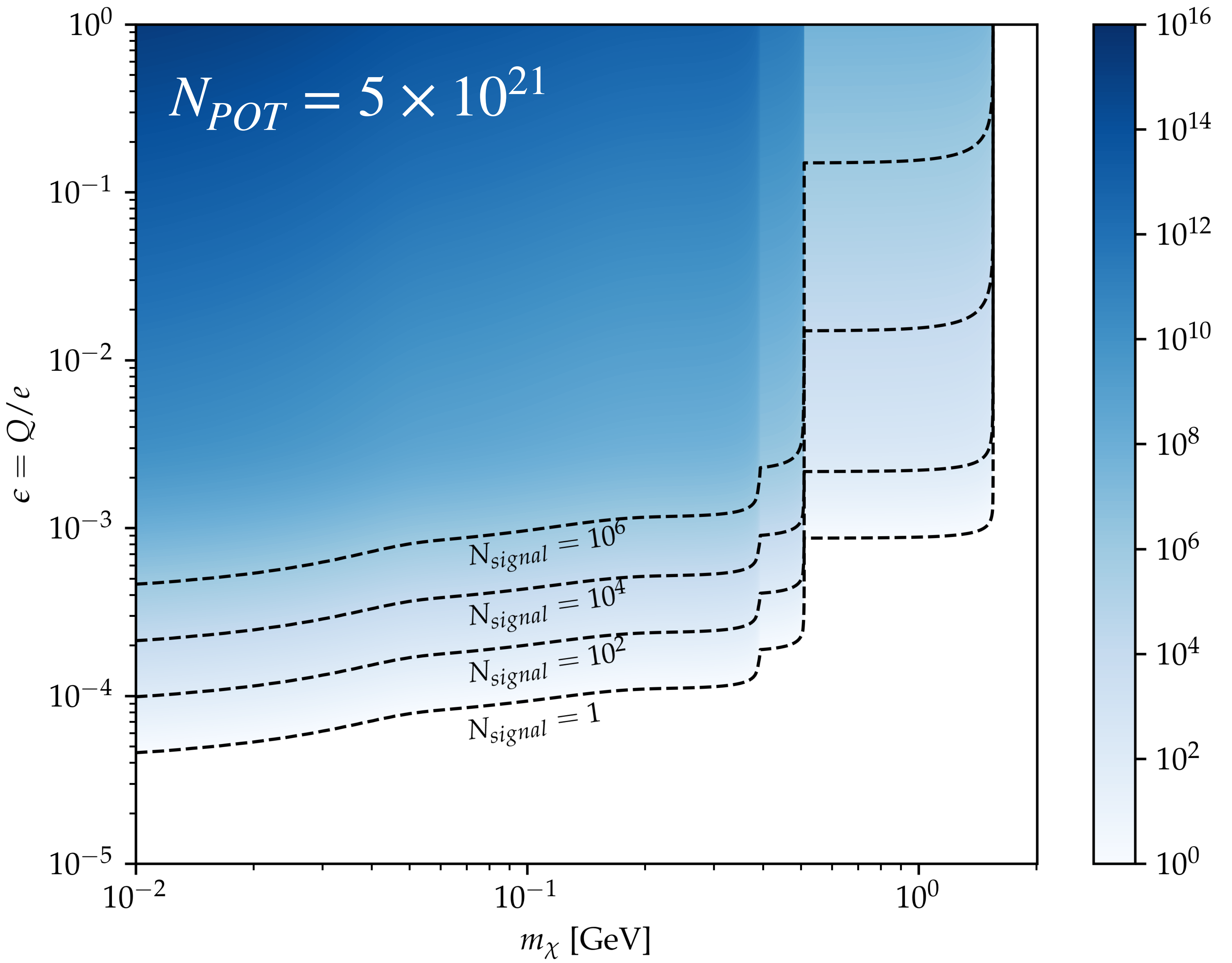
Detection efficiency P

2 = number of layers

$$P = (1 - e^{-N_{PE}})^2$$

Used PMT QE = 30%

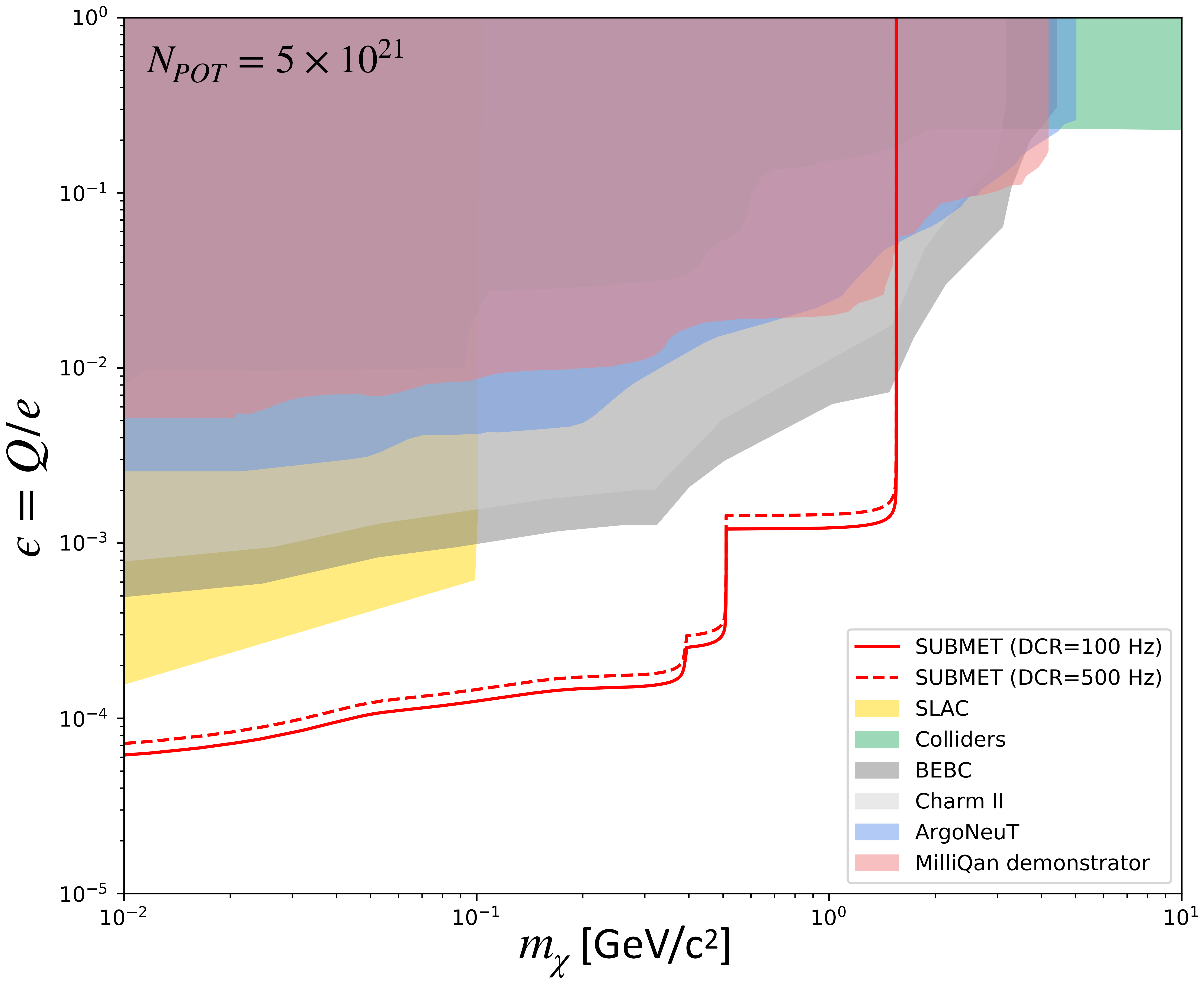
Number of χs detected by SUBMET (N_{signal})



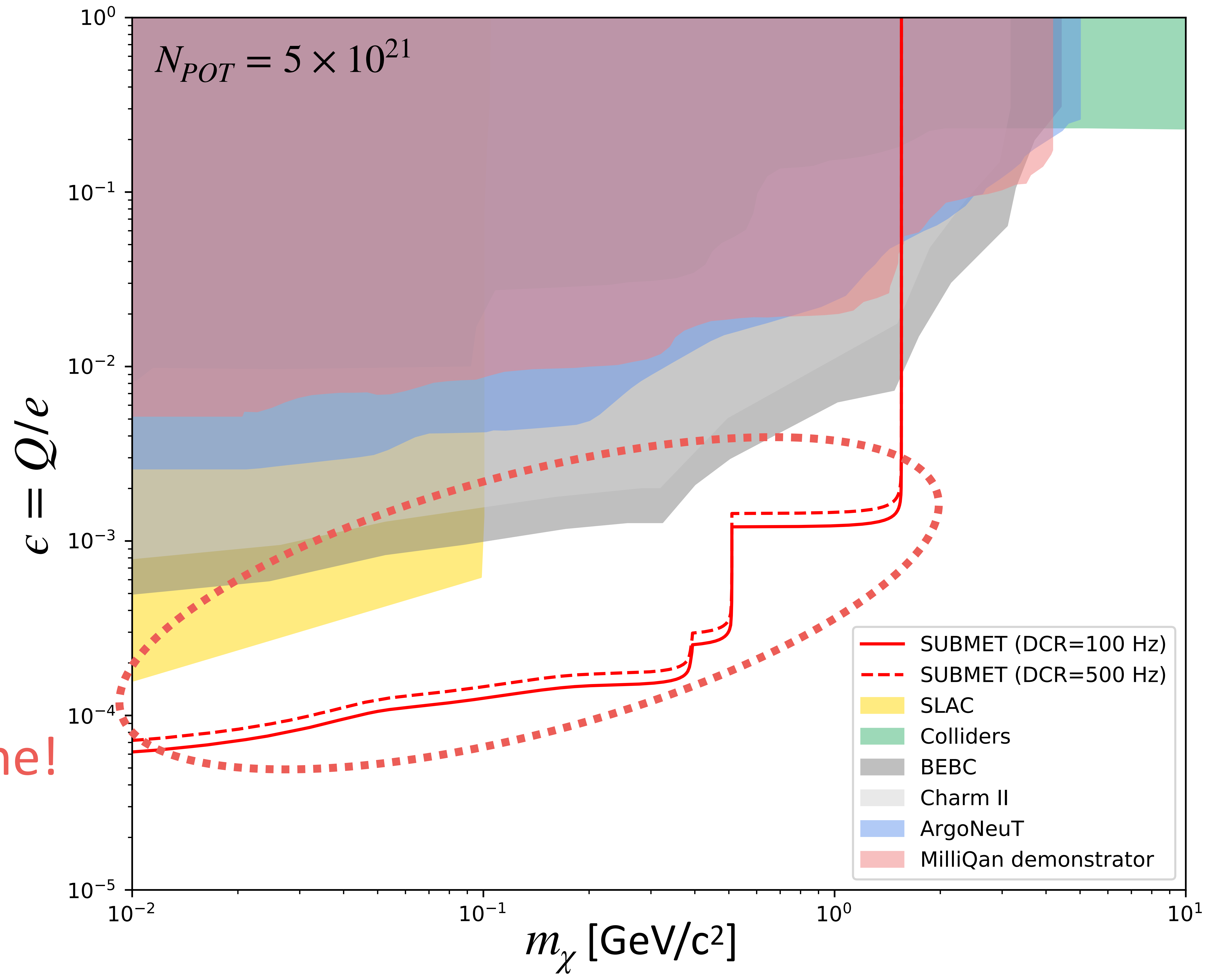
Very steep drop in $\epsilon < 10^{-3}$

→ in this regime, $N_{signal} \propto \epsilon^6$

Sensitivity of SUBMET



Sensitivity of SUBMET

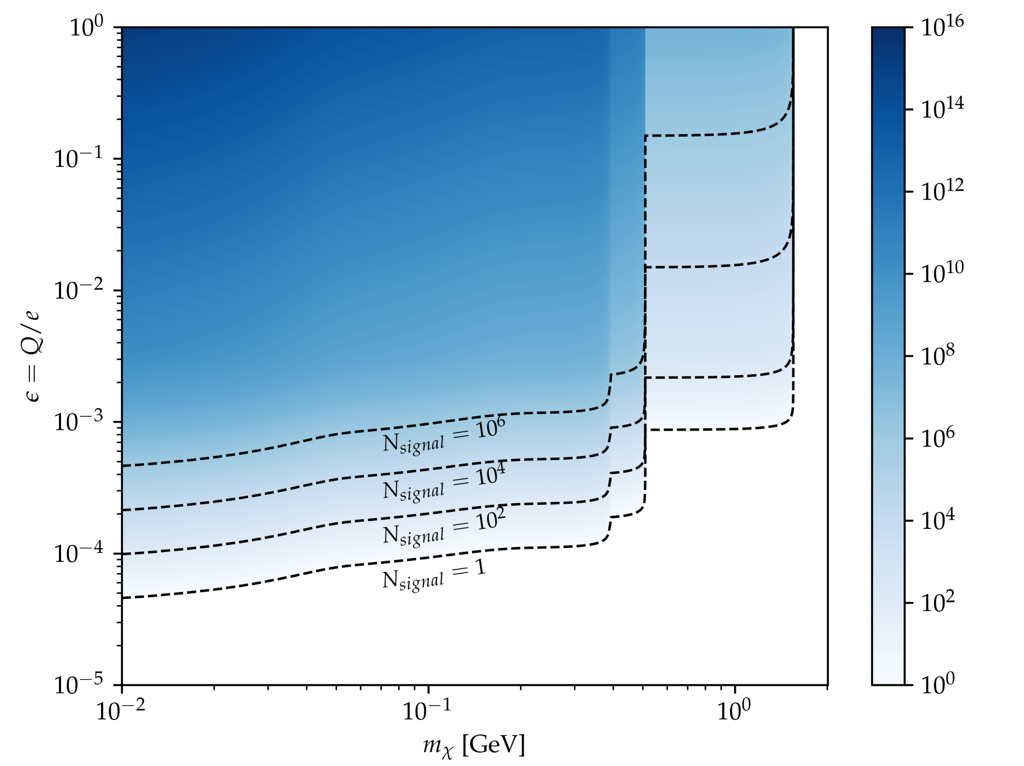


Sensitive to unexplored regime!

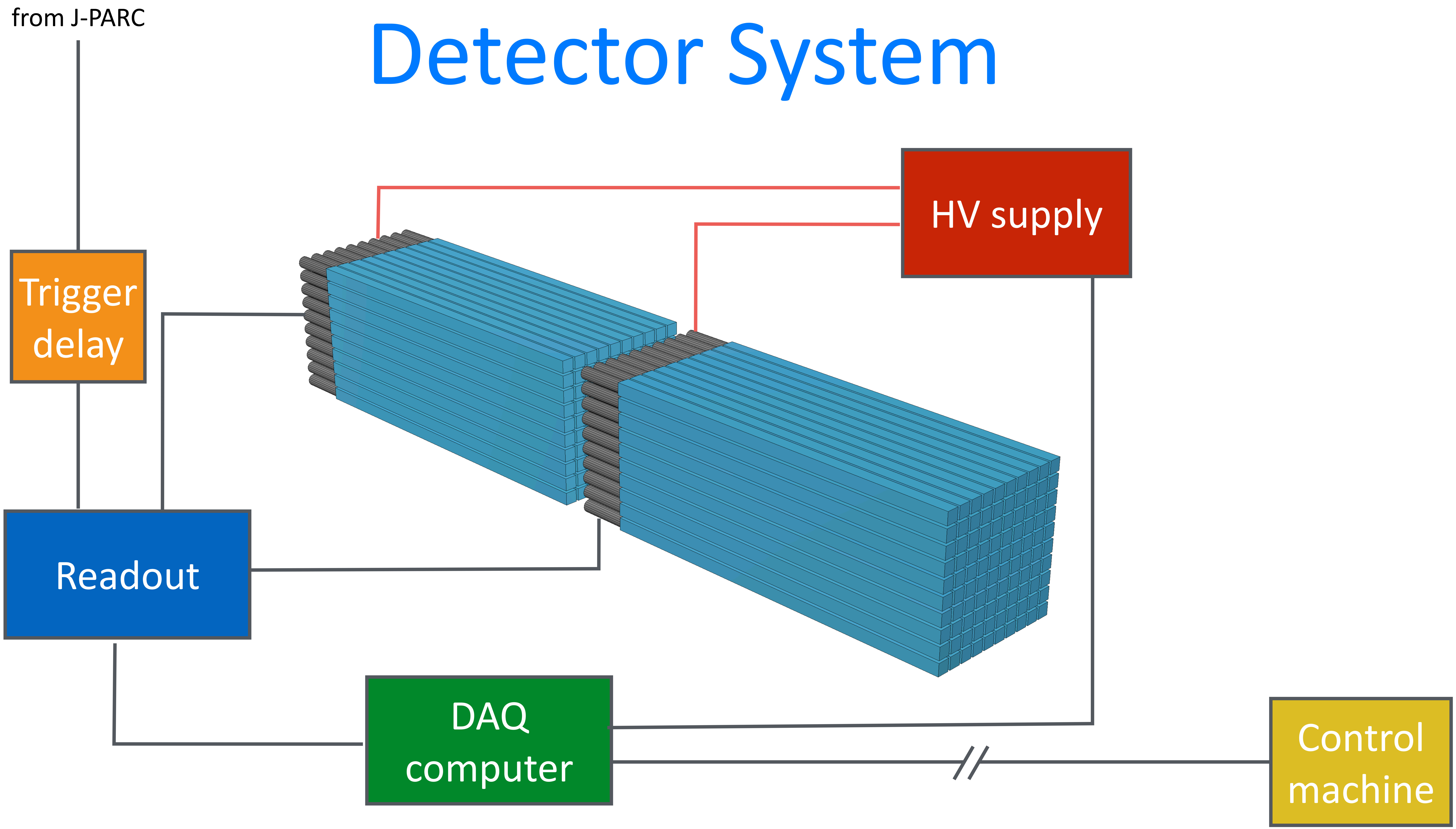
DCR = 100 Hz

DCR = 500 Hz

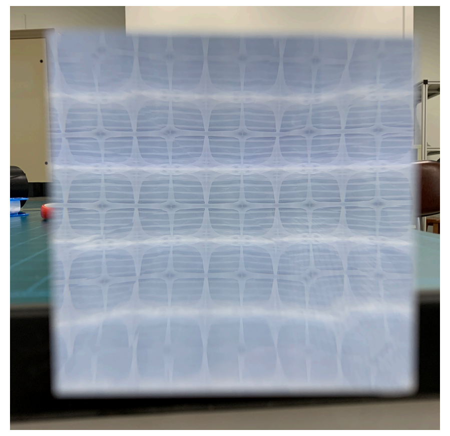
scenarios have similar performance due to the steep drop of N_{signal} in sub-millicharge regime



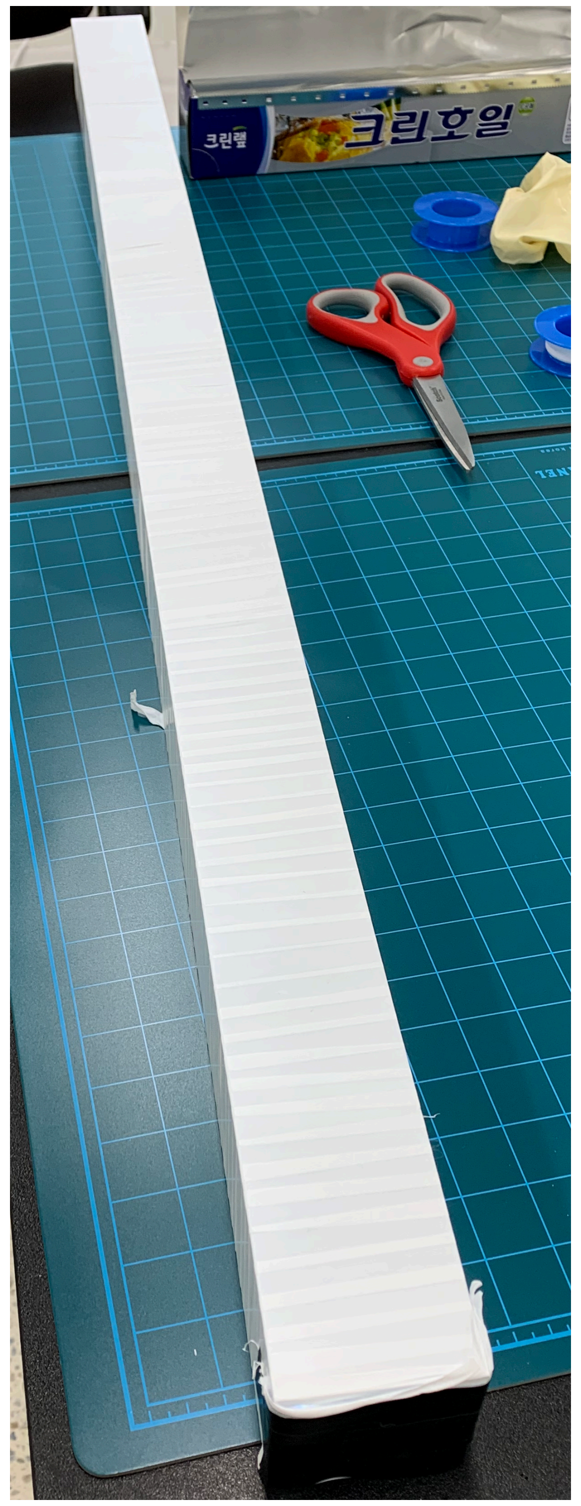
Detector System



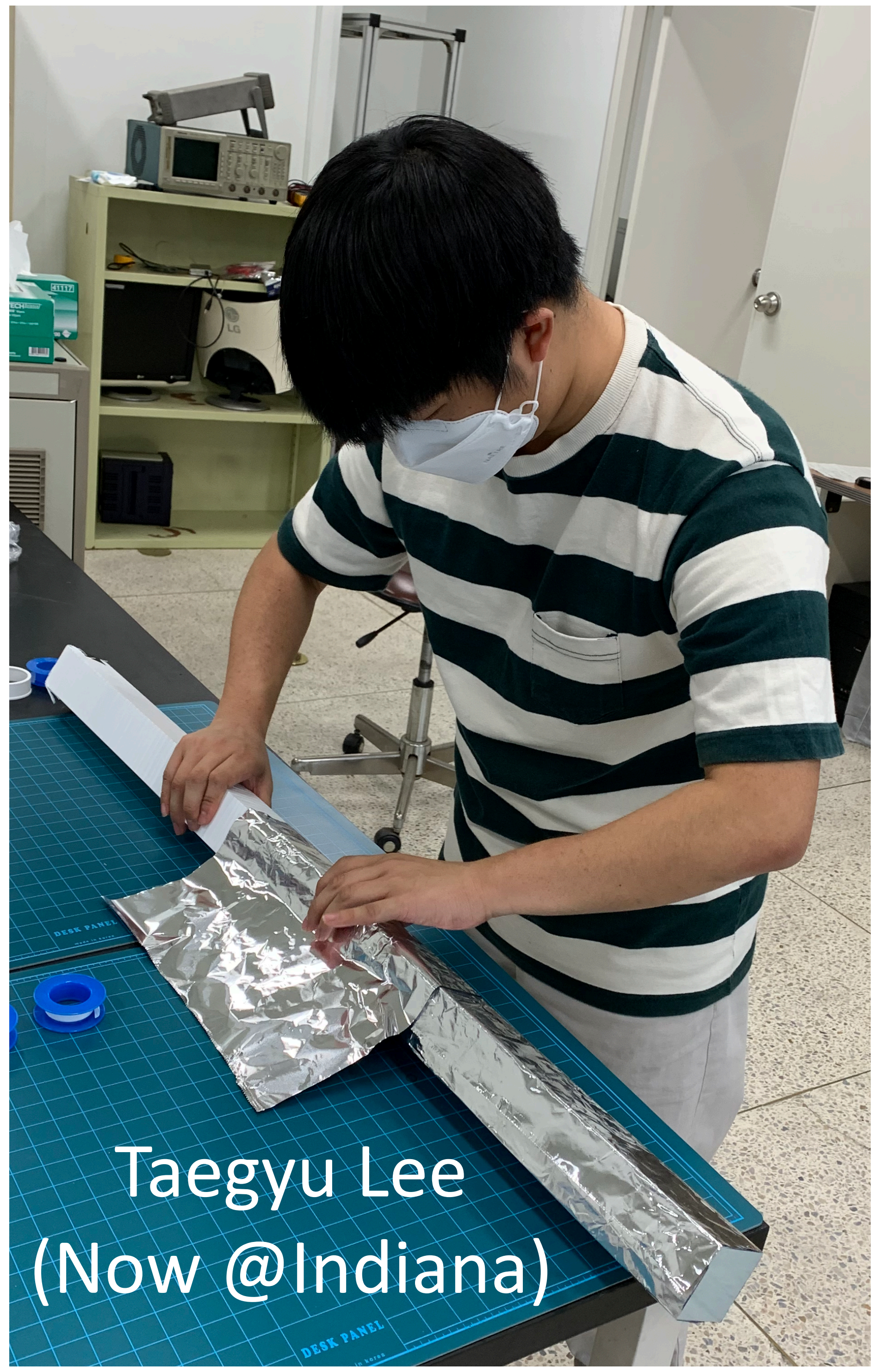
Module Assembly



BC-408

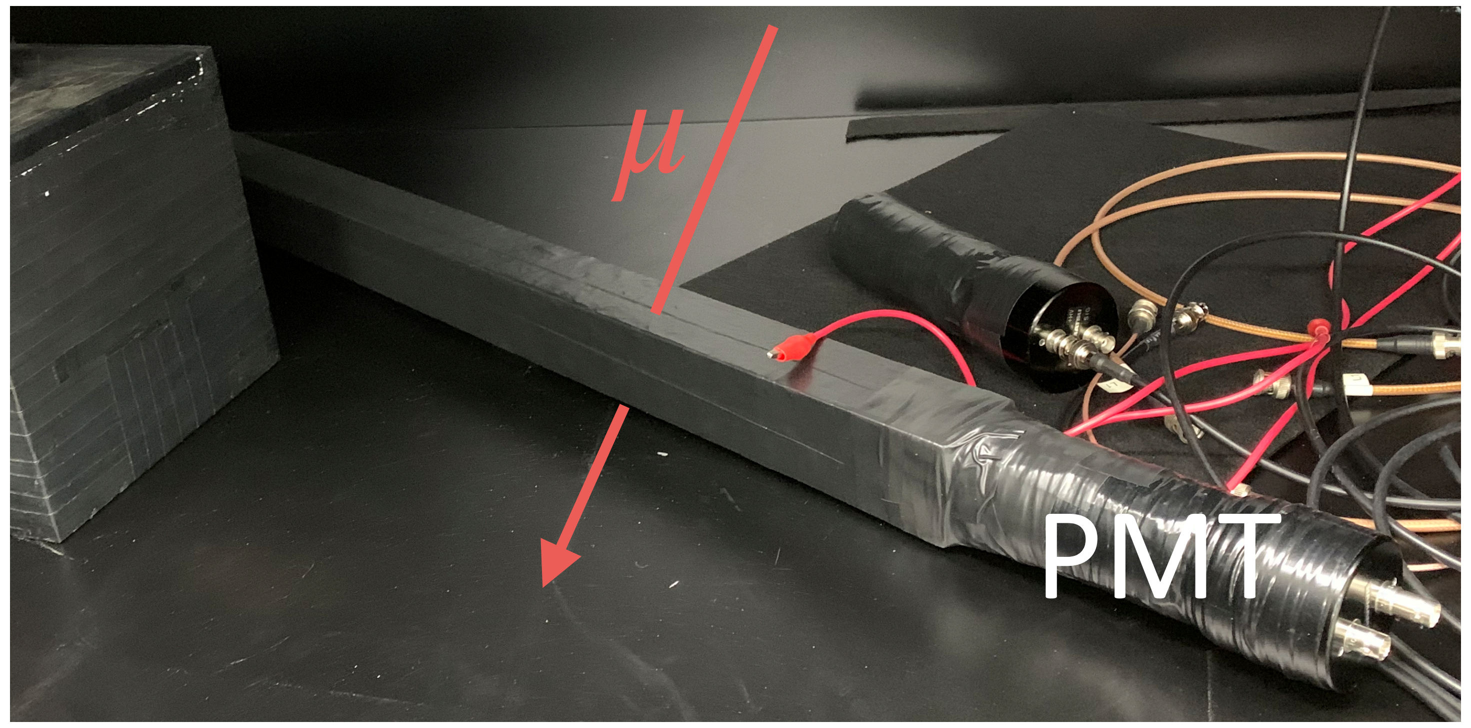


Teflon

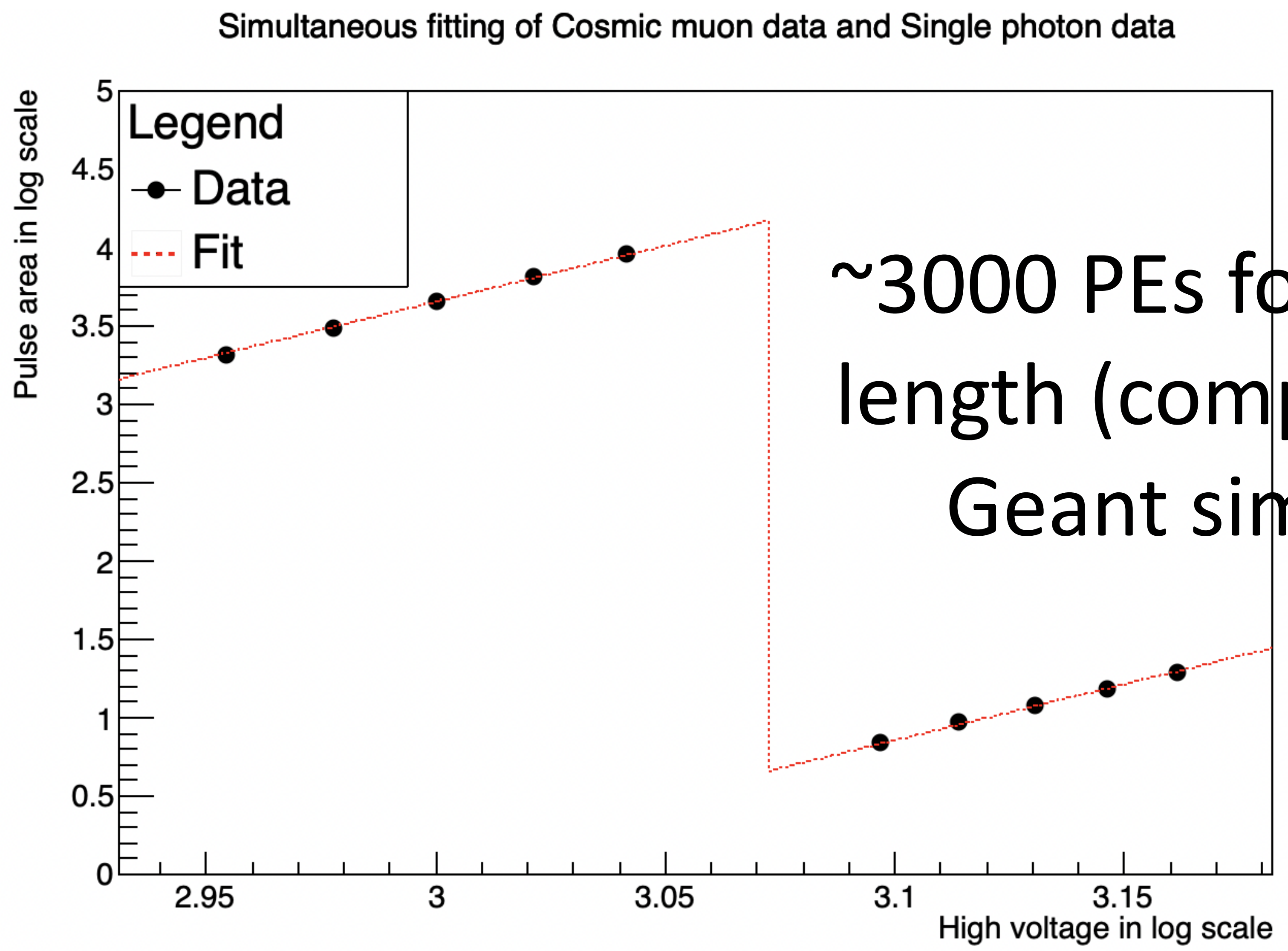


Aluminum foil

black tape

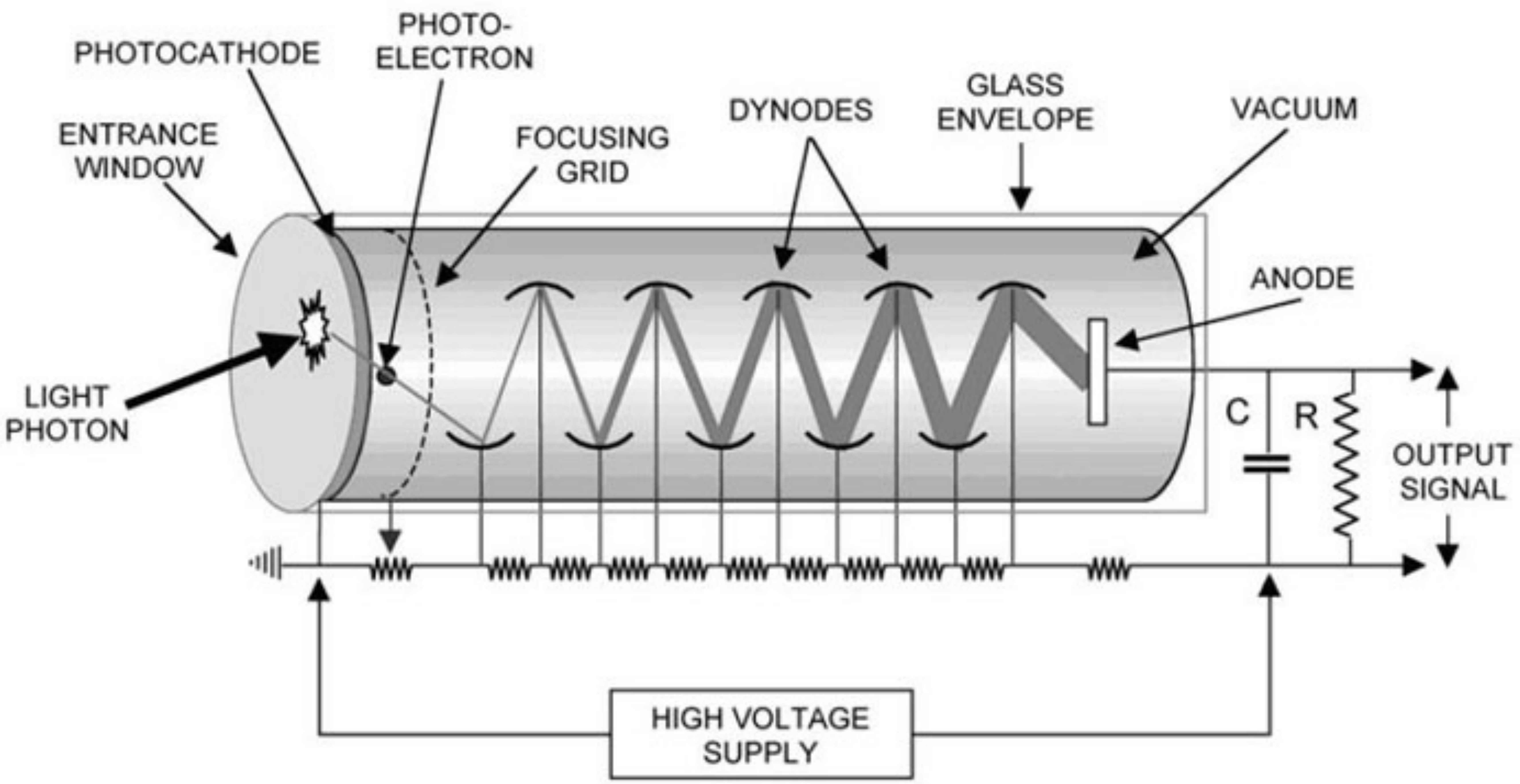


Measured number of photoelectrons by MIP (cosmic muon) by comparing pulse area by MIP and single photon (from LED)



~3000 PEs for 5 cm path length (compatible with Geant simulation)

Photomultiplier

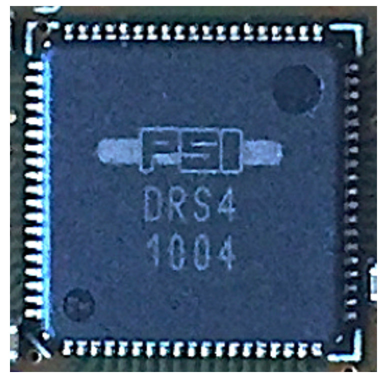


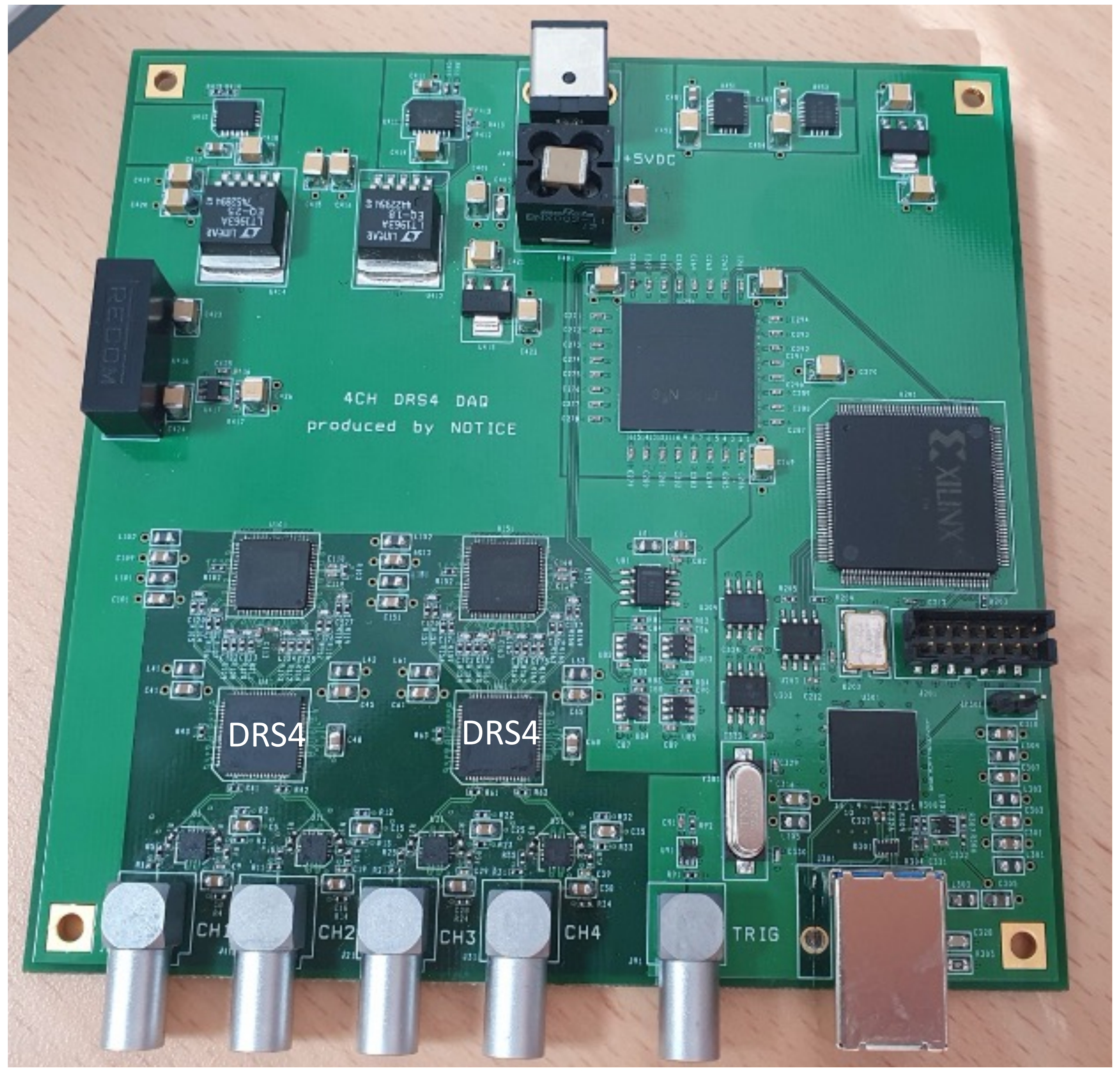
ET9814B

R7725

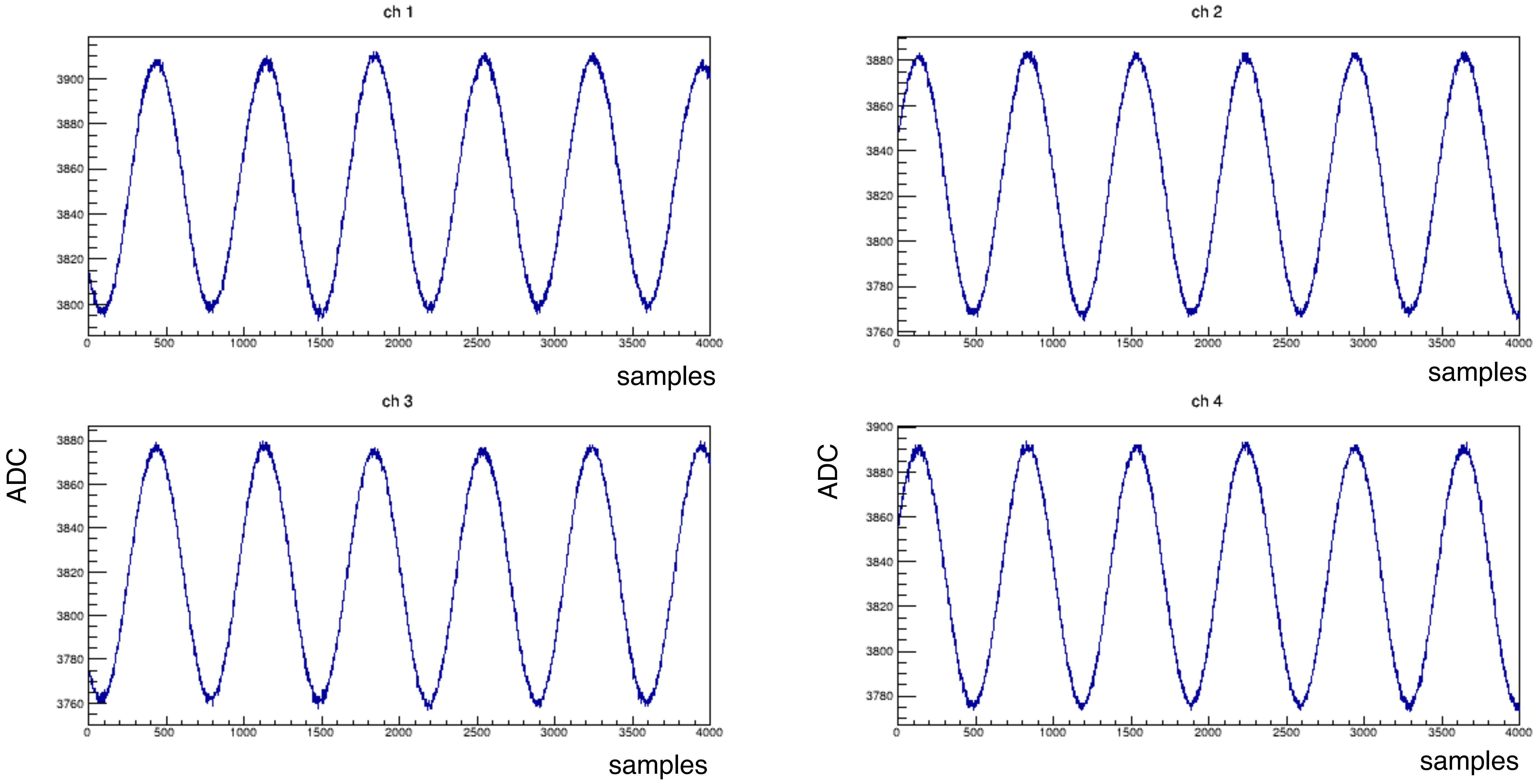
Readout System

DRS4 chip





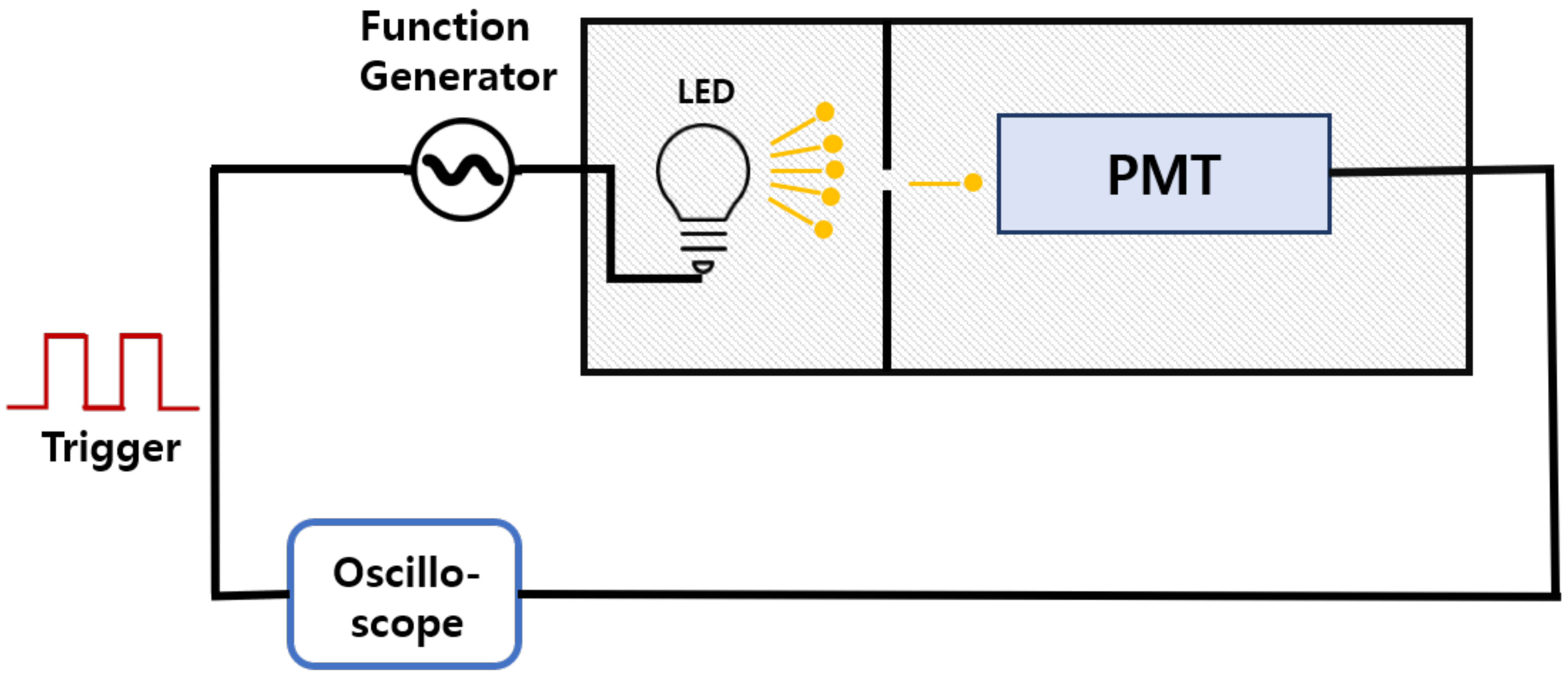
ch1 ch2 ch3 ch4 ext trig



- Testing prototype readout board using DRS4 chips (manufactured by NOTICE KOREA)
- Cascade 4 channels to achieve 4096 sampling depth at 0.7 GSPS (corresponds to 6 us acquisition window)

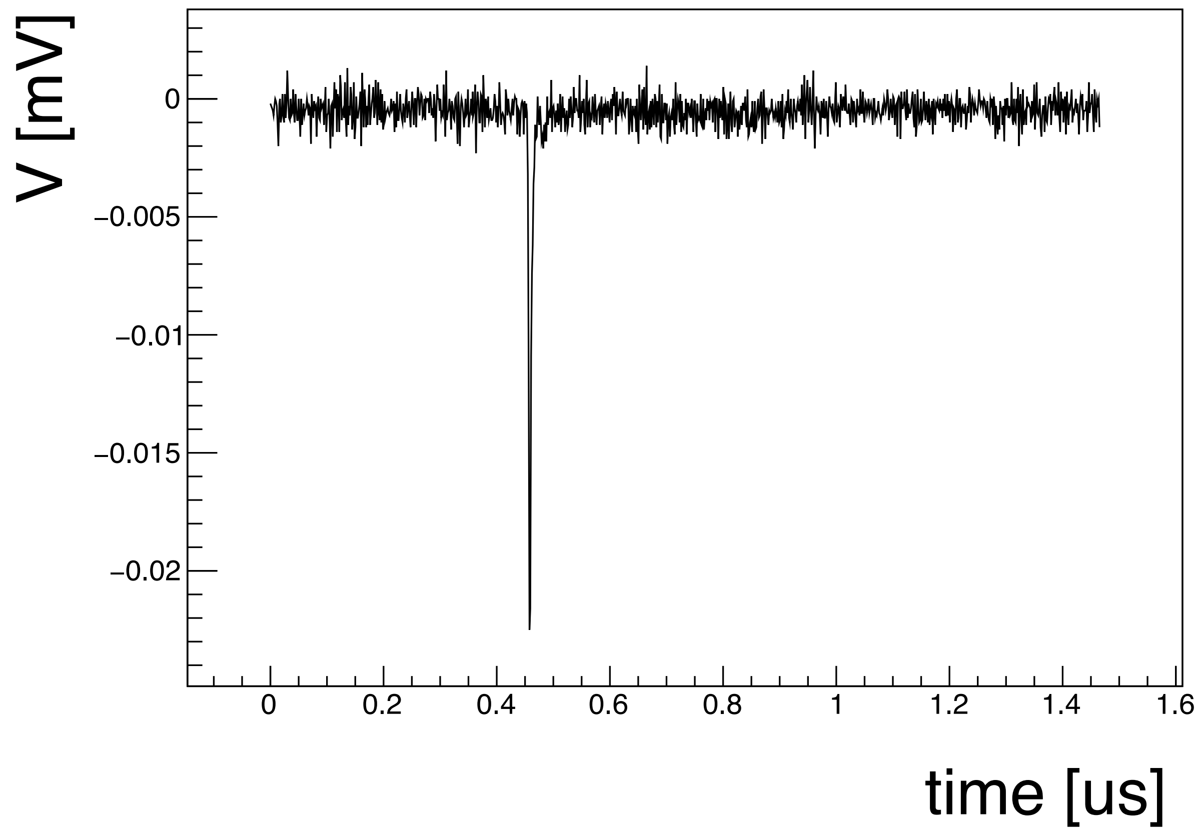
- Test if cascading 4 channels is implemented properly by feeding sine wave from a function generator
- Confirmed continuous sampling for 6 us

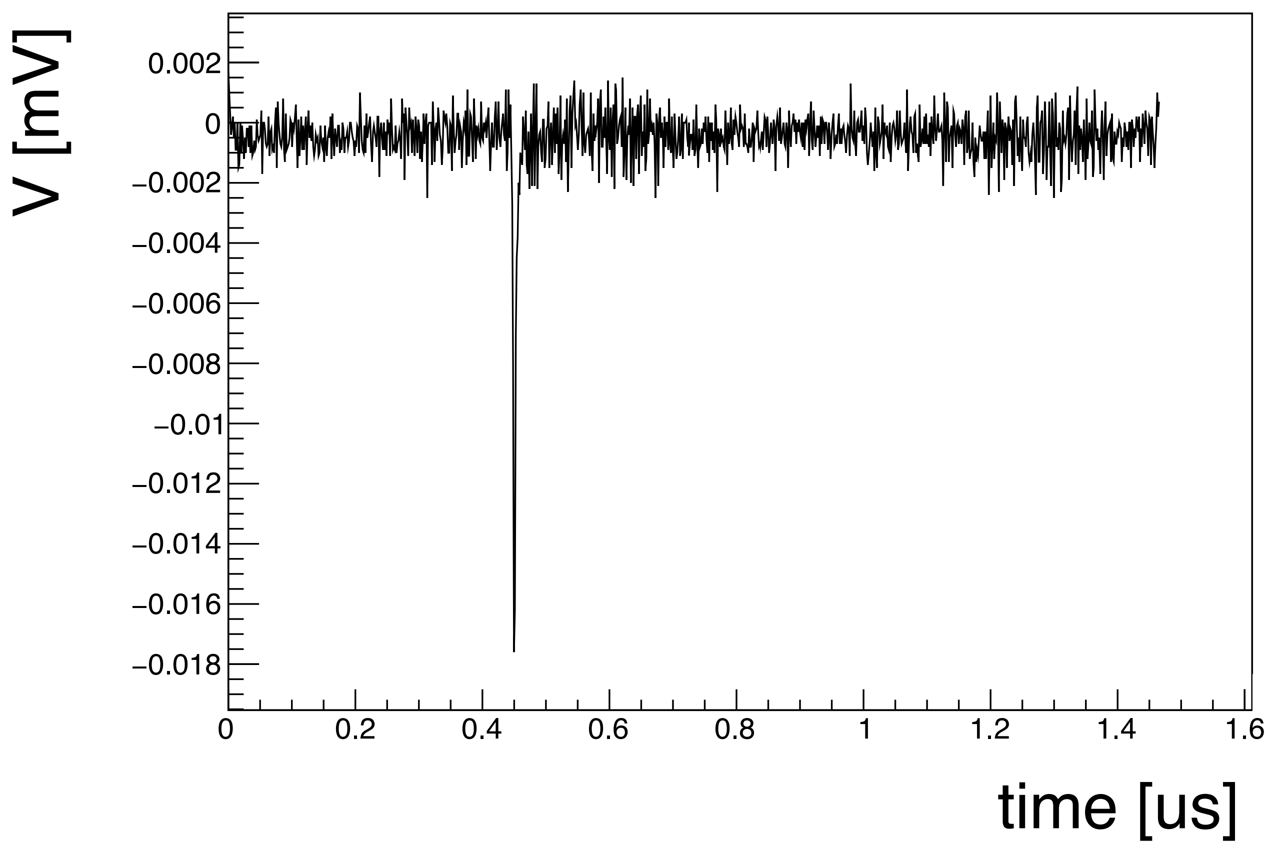
Signal detection efficiency

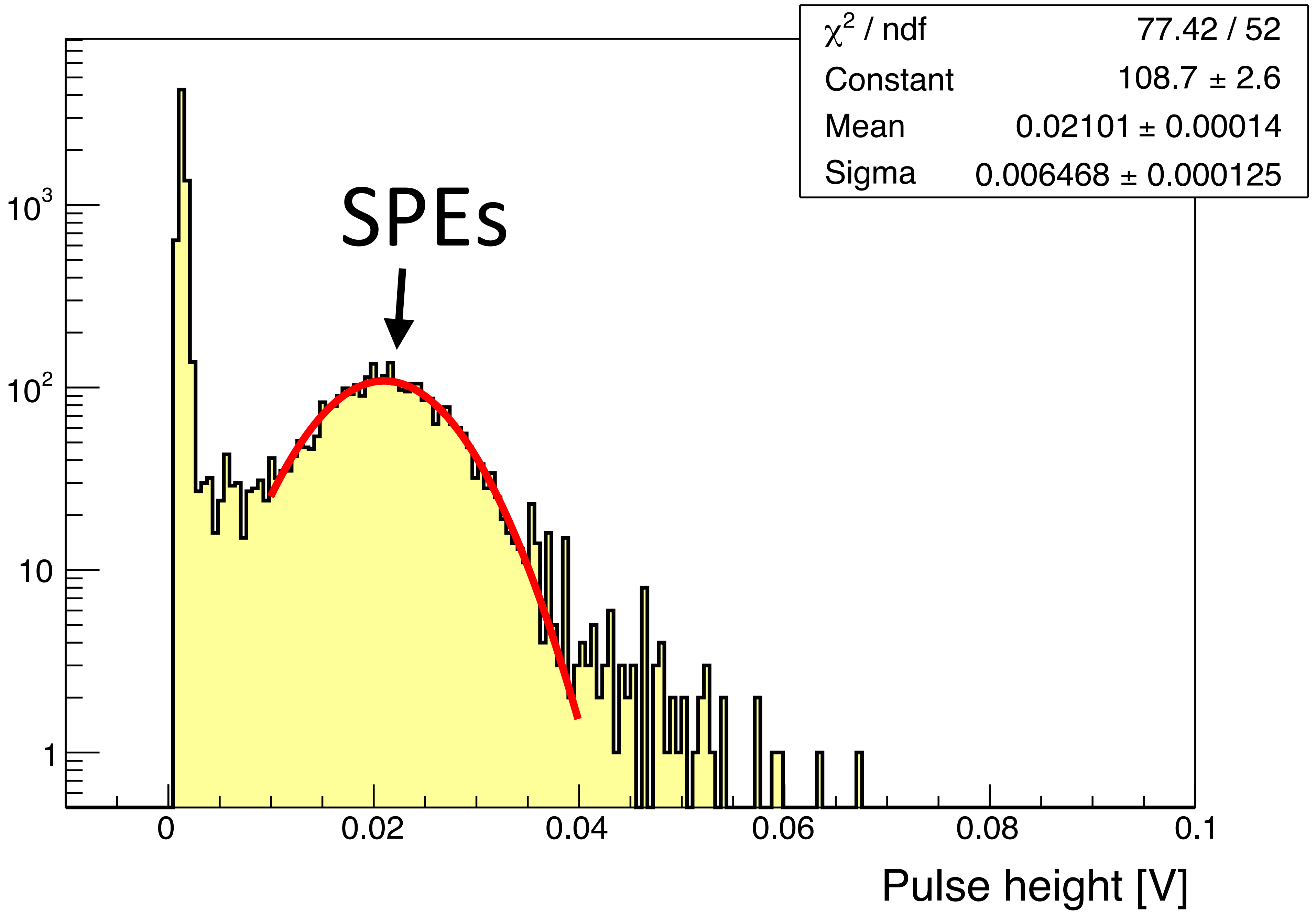


- Estimated sensitivity assumed 100% detection efficiency for SPE signals
- Don't expect inefficiency due to triggering
  - Plan to trigger events using beam signal
- How large is a SPE signal?
  - Shine dim LED on PMT photocathode and measure pulse heights

Signal detection efficiency

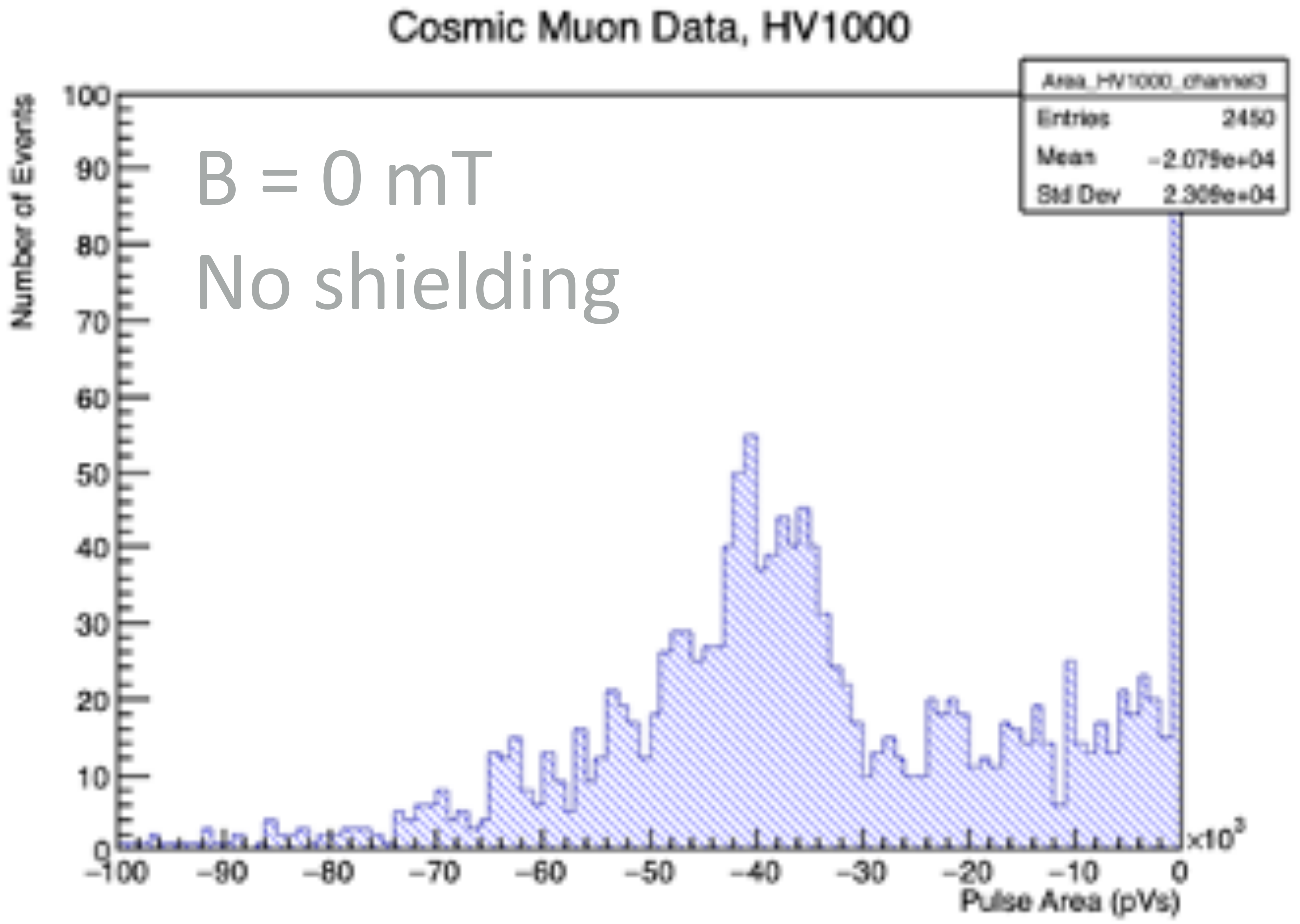


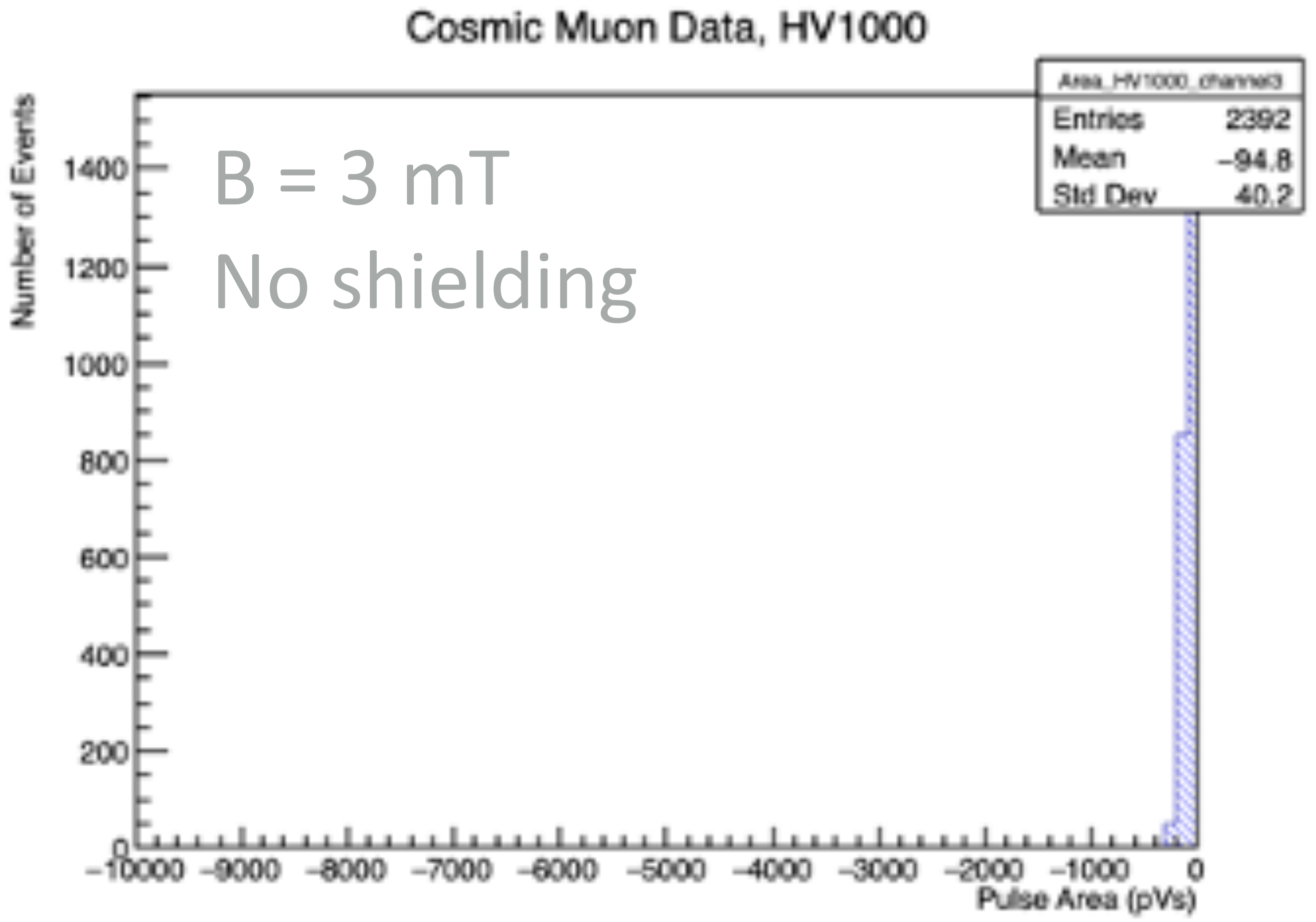


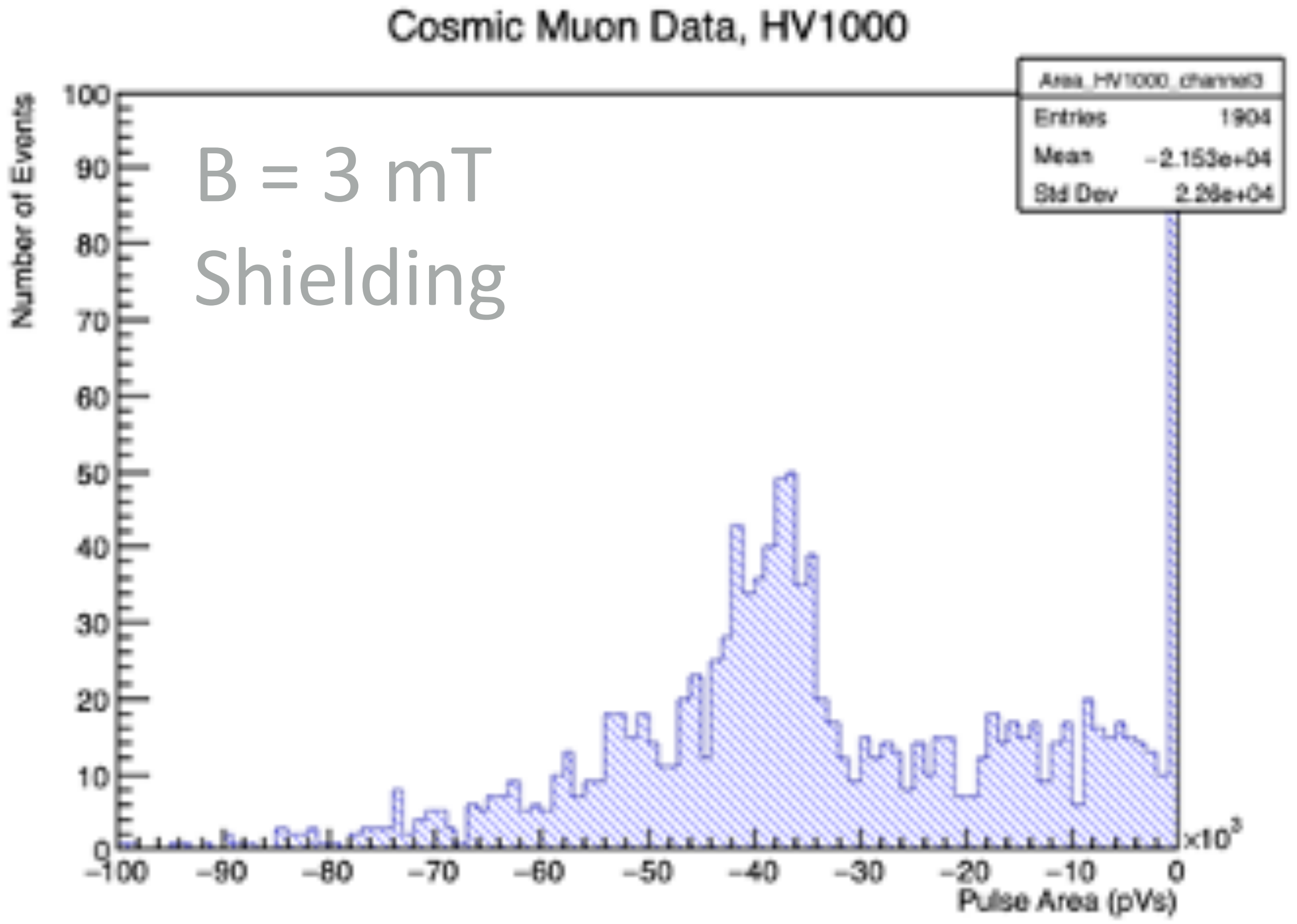


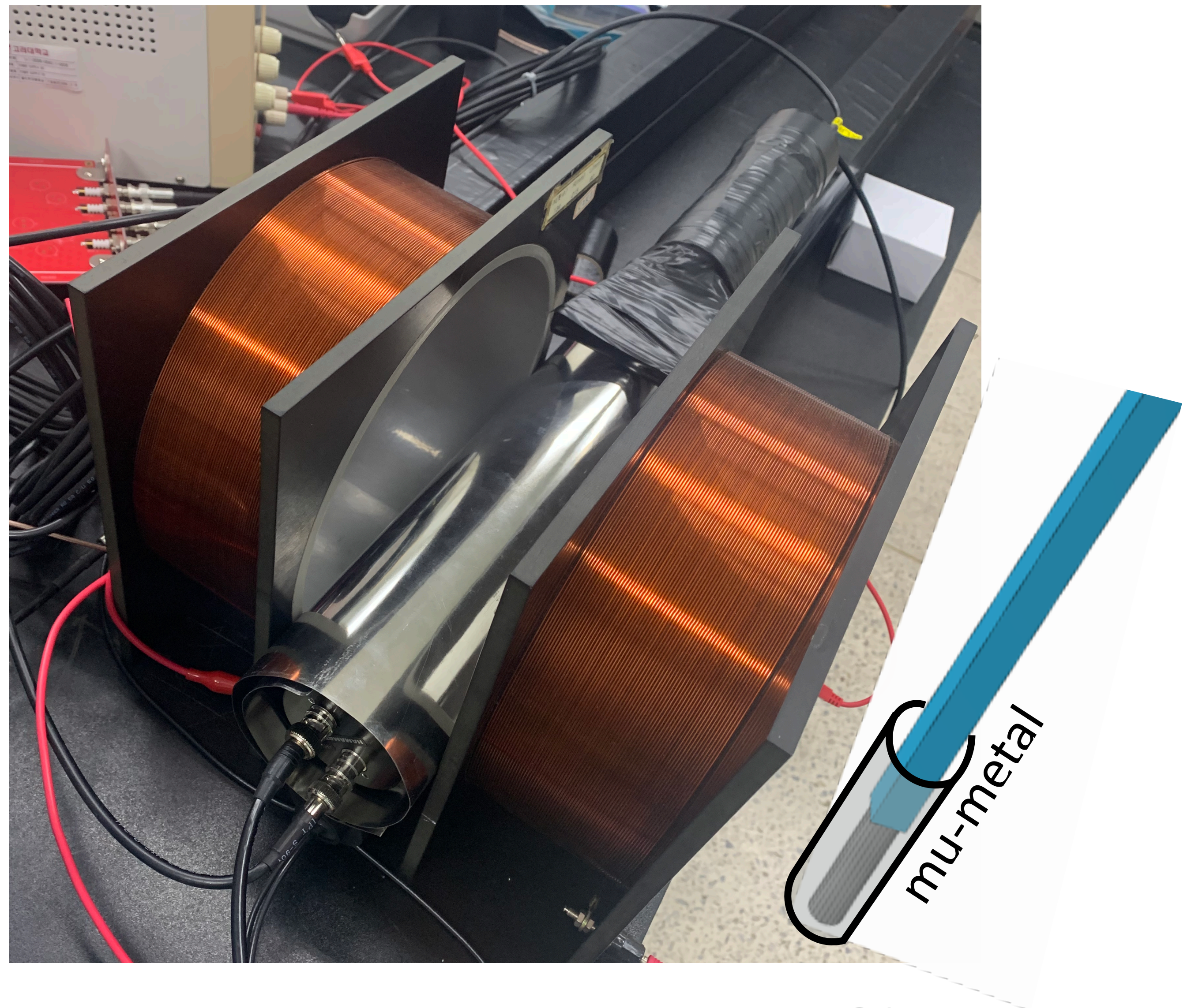
- Typical SPE signals with Hamamatsu R7725 at HV = 1.3 kV (top)
- Average pulse height is 21 mV and width is 6.5 mV (bottom)
- RMS of pedestal of the readout board is <2 mV
- Can select SPE signals with ~100% efficiency

Magnetic field shielding









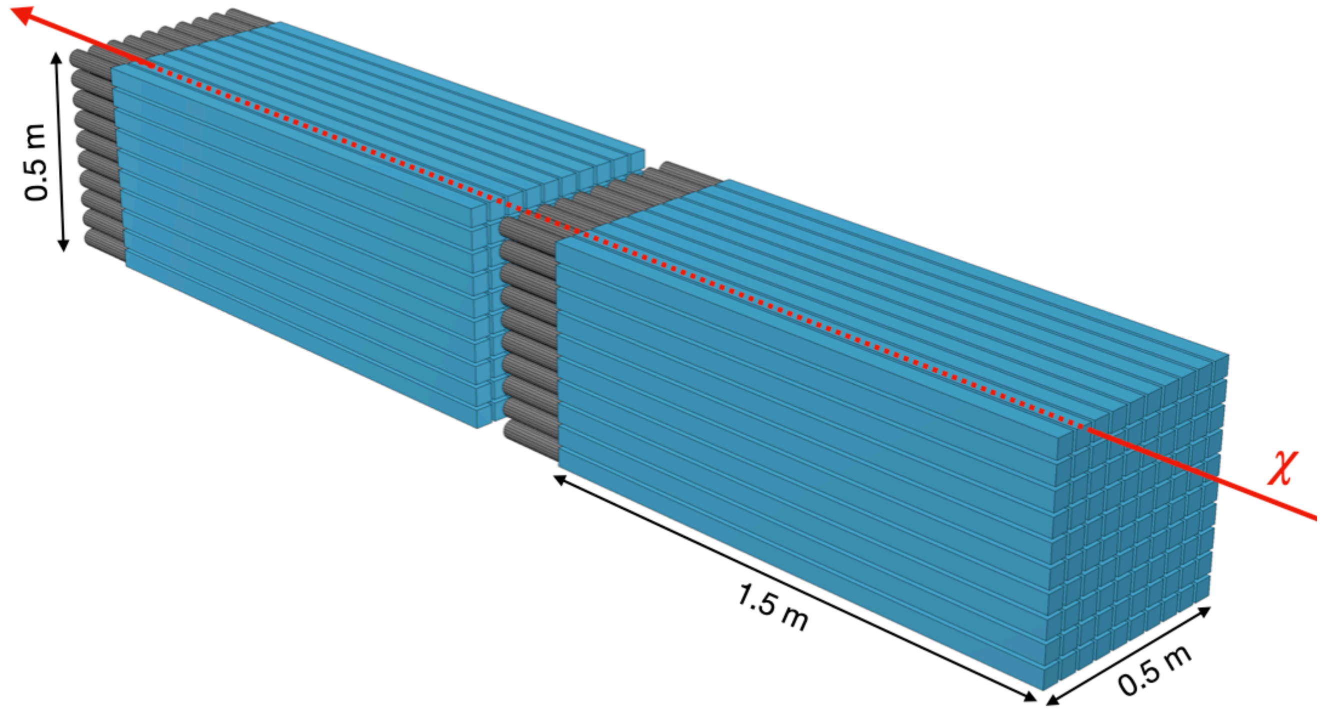
- PMTs are very sensitive to magnetic fields
  - Gain is reduced significantly
- Particularly, when the direction of the field is perpendicular to the PMT axis
- Reduce effect of magnetic field by shielding PMT with mu-metal

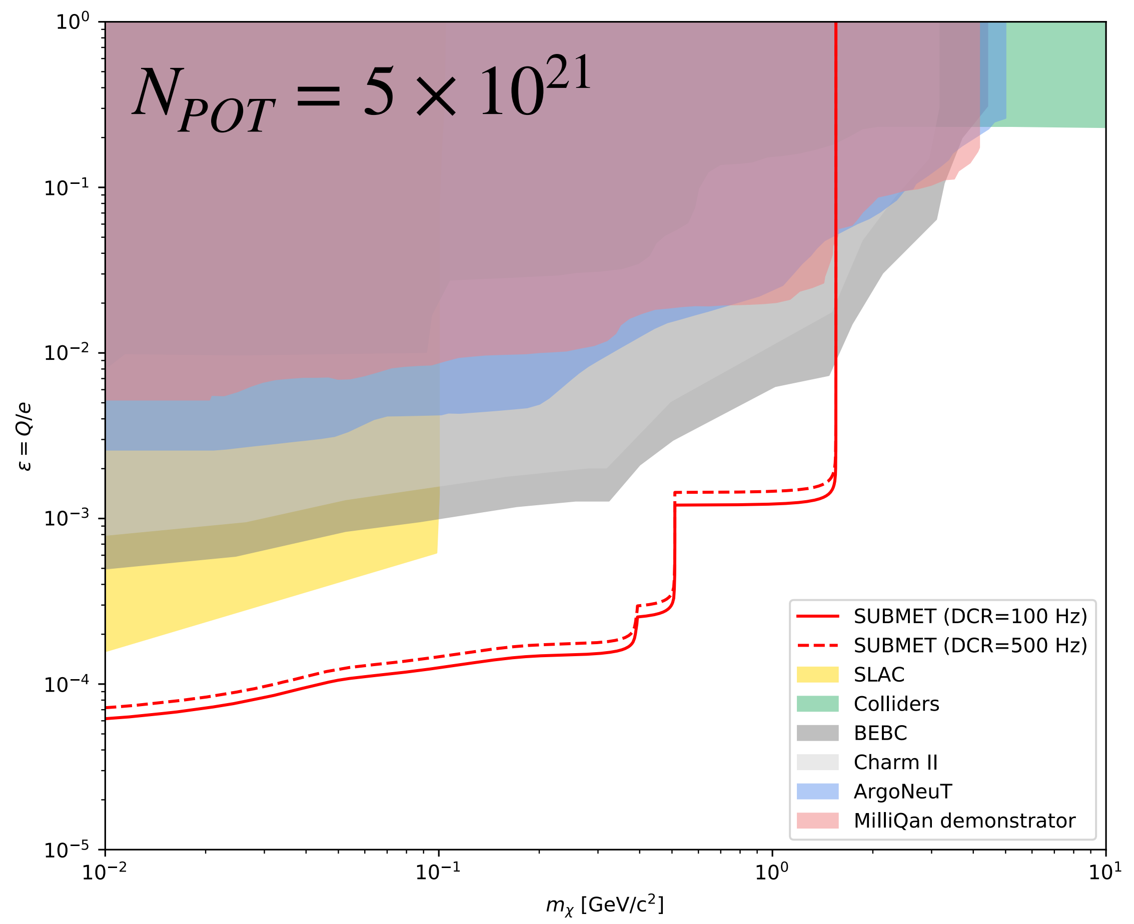
Schedule

- Assuming we get the stage-II approval at the next PAC meeting, the following is a rough schedule of construction and installation of the detector
  - Two steps due to funding availability

Year	2022				2023			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Construction								
Installation								
Operation								

Summary - SUMET





- We propose a **new experiment to search for millicharged particles** using 30 GeV proton beam at **J-PARC**
- Unique opportunity to **probe low mass** ($m_\chi < 1.6$ GeV) millicharged particles
  - Sensitive to χs with $\epsilon = 6 \times 10^{-5}$ in $m_\chi < 0.2$ GeV and $\epsilon = 10^{-3}$ in $m_\chi < 1.6$ GeV with $N_{POT} = 5 \times 10^{21}$
  - Can set the leading limit even with a couple of months of data
- Plan: construct/install the detector before the proton beam later this year!

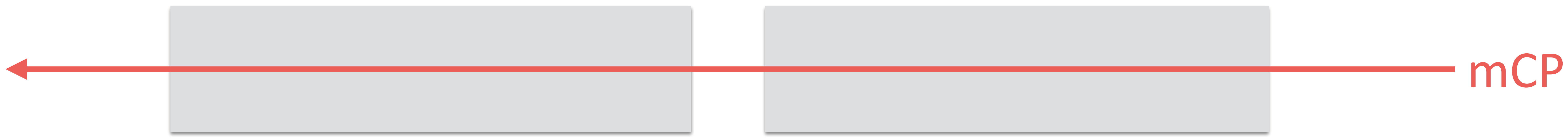
https://www.unitypaloalto.org/leave-no-stone-unturned-with-rev-john-riley/

https://www.unitypaloalto.org/leave-no-stone-unturned-with-rev-john-riley/

We don’t know where new physics is hidden

Leave no stone unturned!

https://www.unitypaloalto.org/leave-no-stone-unturned-with-rev-john-riley/



Production of milli-charged particles (mCP) is proportional to ϵ^2 where $\epsilon = Q/e$. Detection efficiency per scintillator (P) for particles with $\epsilon \leq 10^{-3}$ is approximately proportional to ϵ^2 as well. The acceptance of the detector is A. The detector is composed of two scintillator layers $(n = 2)$ as shown in the cartoon. For $\epsilon = 10^{-3}$, the number of mCPs produced at collisions is N_{-3} and the detection efficiency P is 1.

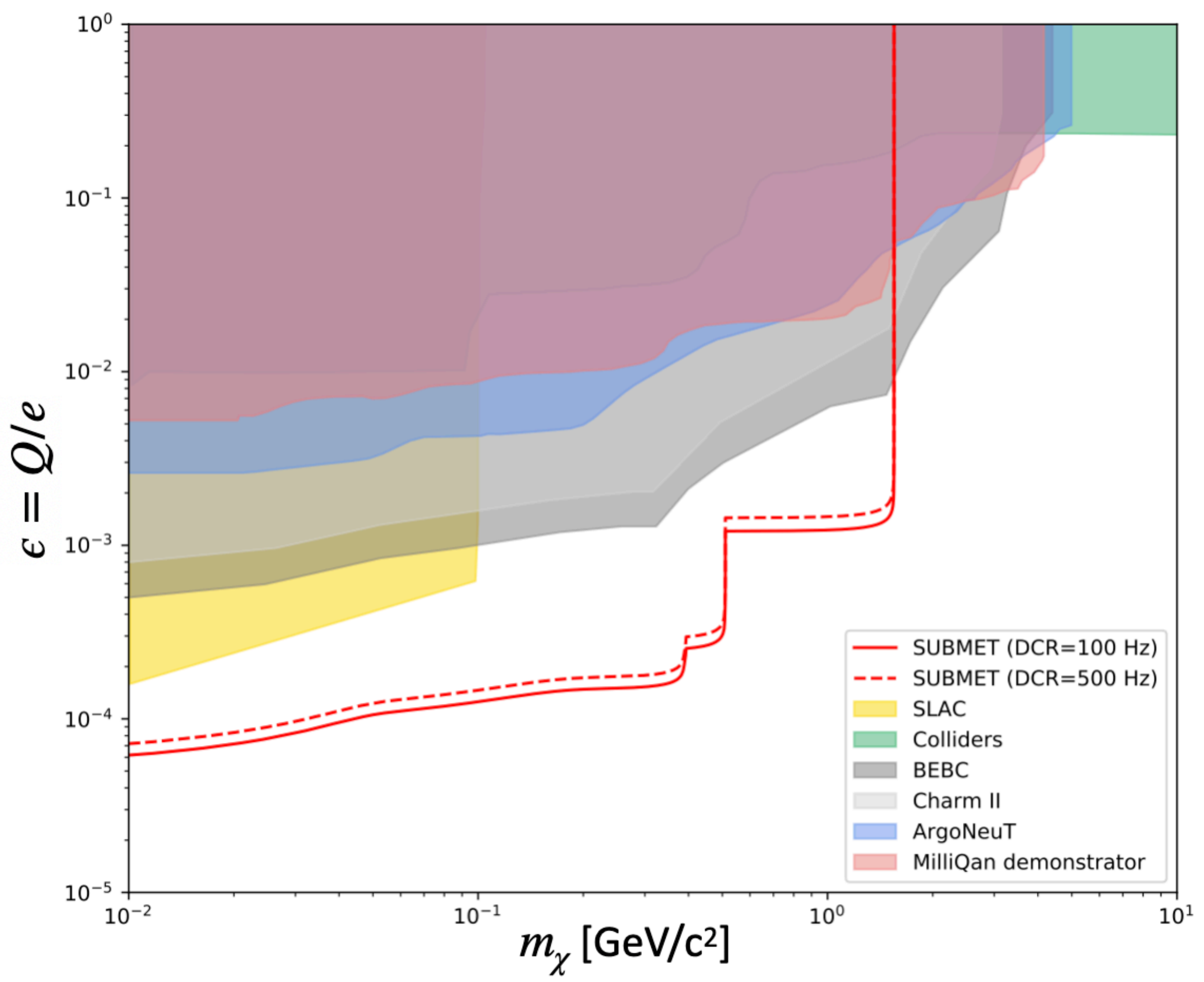
1. If $N_{sig} = N_{-3}A = 10^{10}$, what is the number of events that contain hits in two layers at the same time? Assume that there is one mCP per event.

2. What is N_{sig} for $\epsilon = 10^{-4}$?

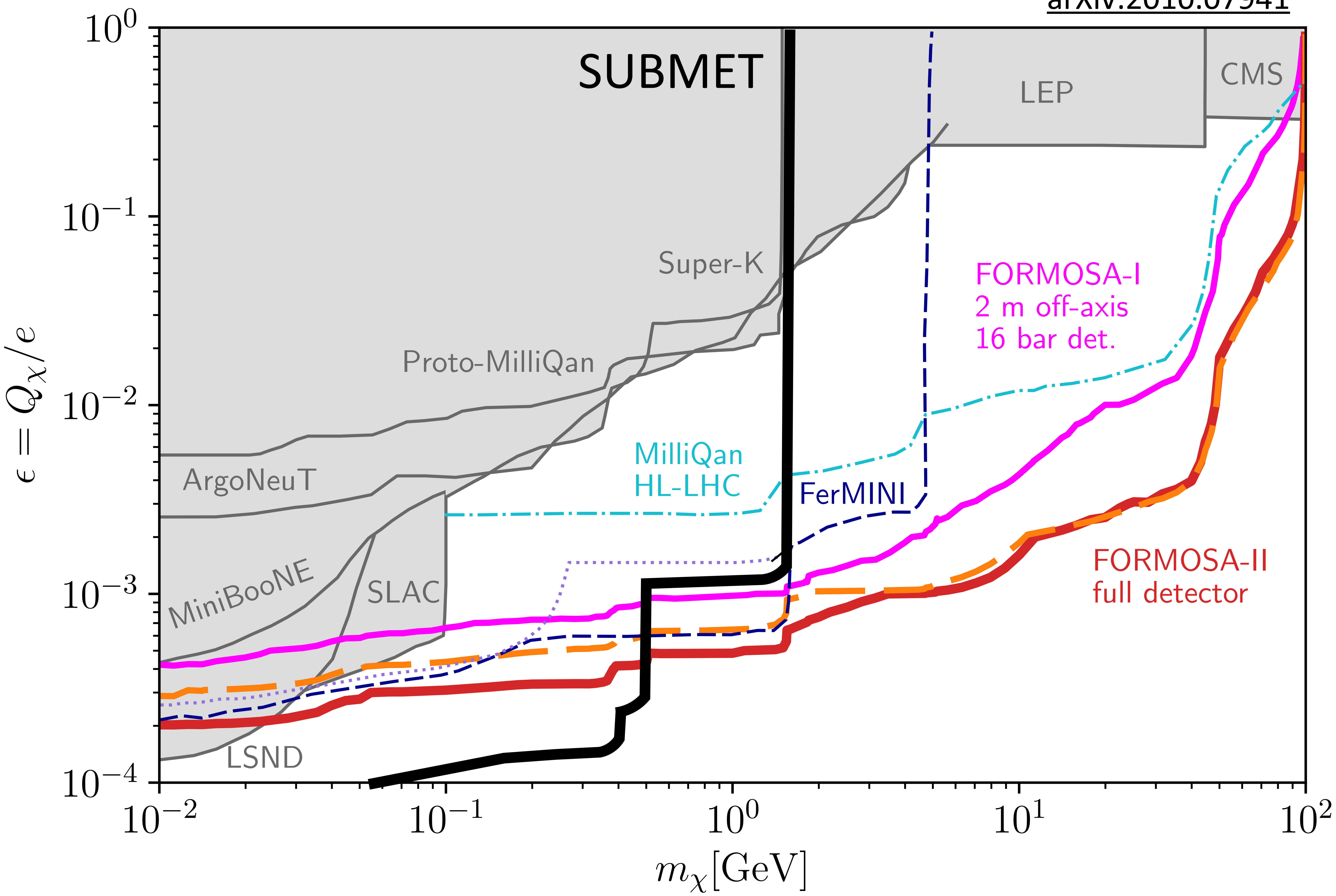
3. If the expected background events is 10, how many observed signal events do you need to exclude your model at 95% CL (p-value = 0.05)? Use Poisson as your likelihood.

4. In this case, what is the corresponding value of ϵ?

Other proposals/experiments



arXiv:2010.07941



There are proposals at LHC (milliQan, FORMOSA) and at FNAL (FerMINI), which are sensitive to higher mass regime → complimentary

The team

Sungwoong Cho
Suyong Choi
Jeong Hwa Kim
Eunil Won
Jae Hyeok Yoo
Hoyong Jeong
Hyunki Moon

Claudio Campagnari
Matthew Citron
David Stuart
Ryan Schmitz

Christopher S. Hill

Andy Haas

Jihad Sahili
Haitham Zaraket

Albert De Roeck
Martin Gastal