Precision Measurements of Diffractive Dissociation and Lepton Flavor Universality

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What is the origin of matter and the universe

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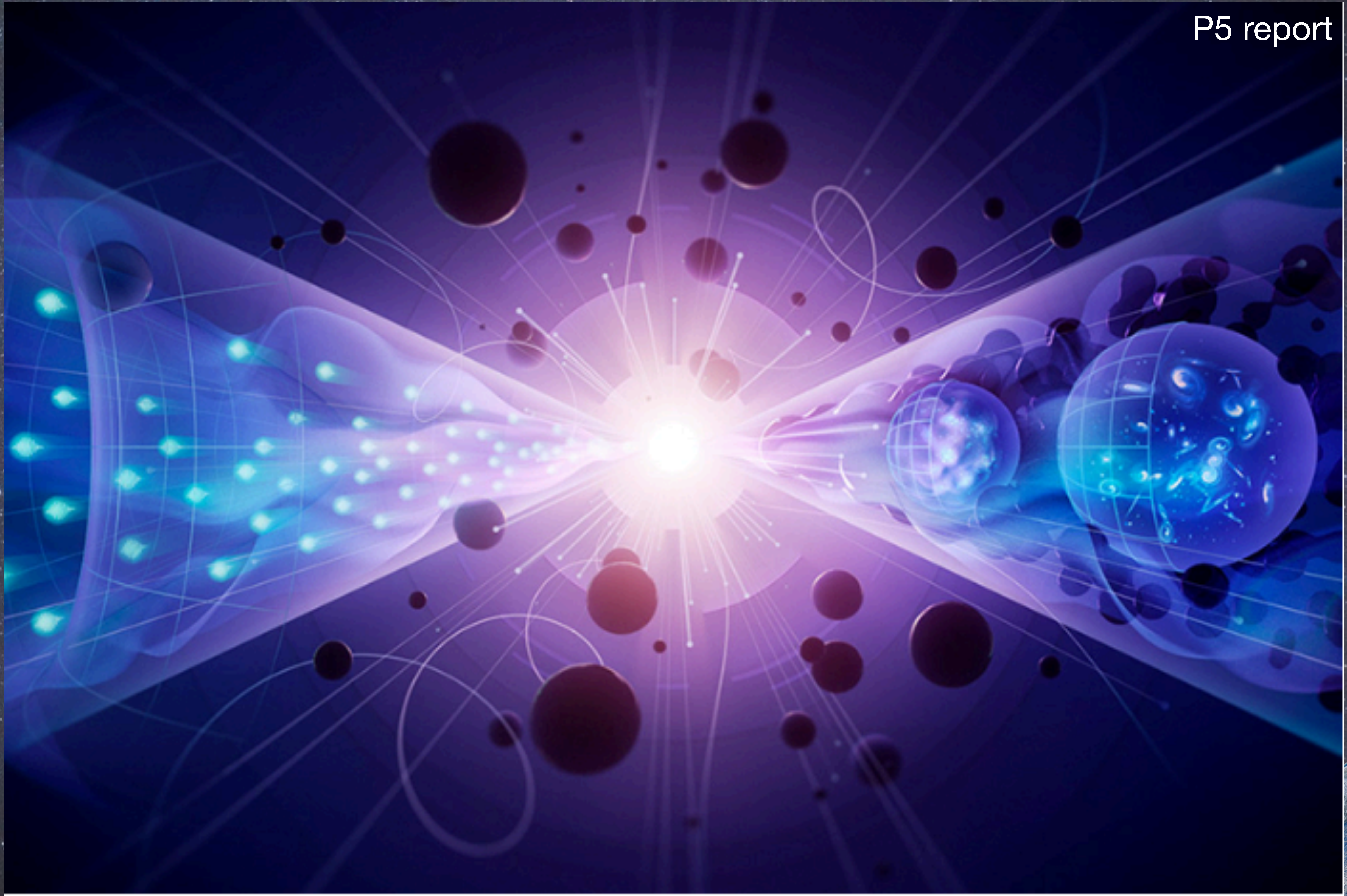

P5 report

Back to the beginning of the universe

Contents

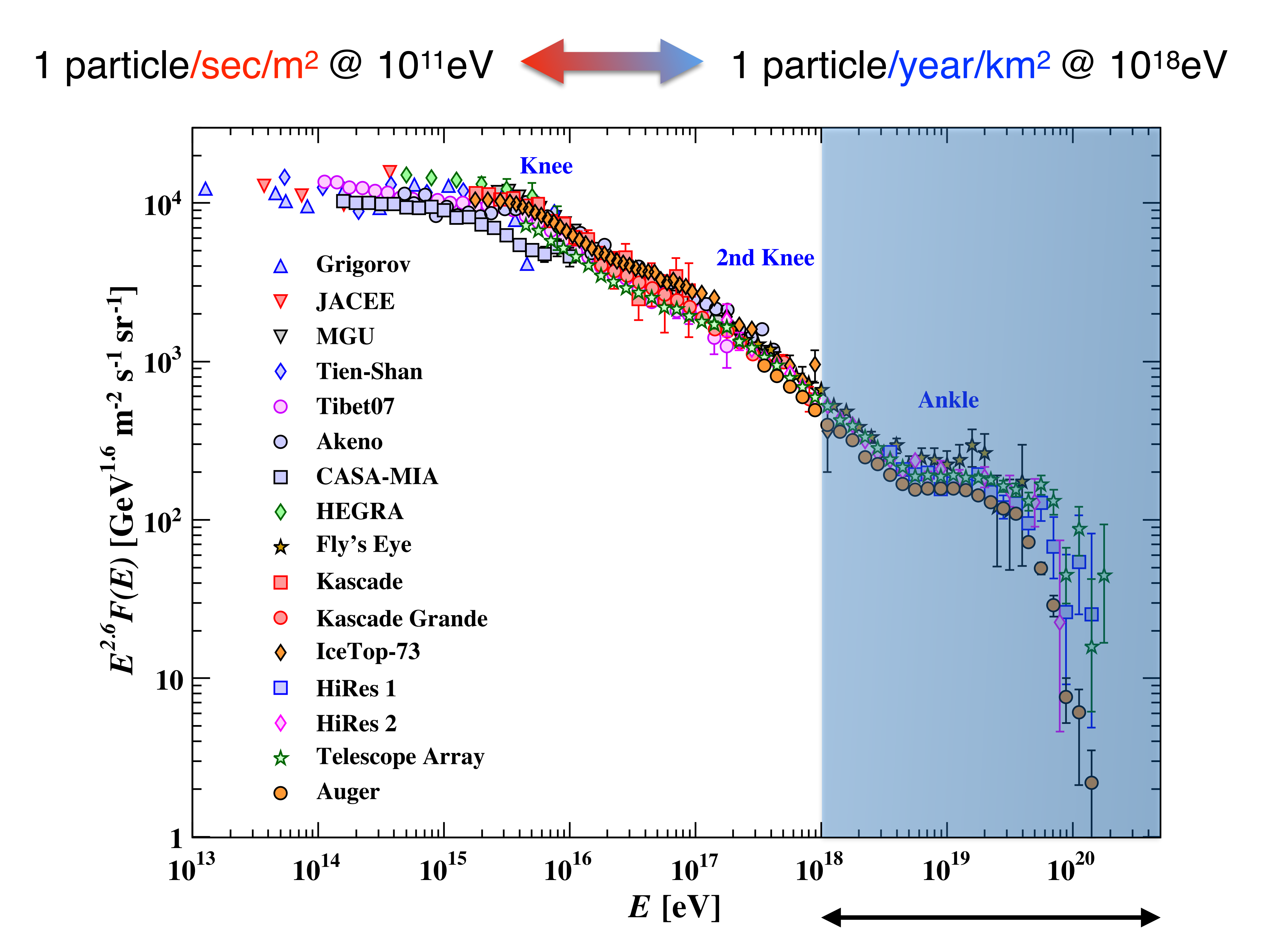
- ✦ Diffractive Dissociation
  - ✦ Introduction of ultrahigh-energy cosmic-rays (UHECRs)
  - ✦ The LHCf experiment and ATLAS-LHCf common experiment
  - ✦ Measurements of forward photon production, and low-mass diffractive photon production
  - ✦ Discussion about the impact of ATLAS-LHCf joint analysis result to the determination of mass composition of UHECRs

- ✦ Lepton Flavor Universality (LFU)
  - ✦ New physics search with testing LFU
  - ✦ The Belle II experiment
  - ✦ Measurements of LFU with semileptonic B decays
  - ✦ Impact of LFUV to the new physics search

What is the origin of UHECR

Source candidates:
- ✦Active Galactic Nuclei (AGNs)
- ✦Gamma Ray Burst (GRBs)
- ✦…

Objective：explore the origin of Ultrahigh Energy Cosmic-Ray ($E>10^{18}$ eV)



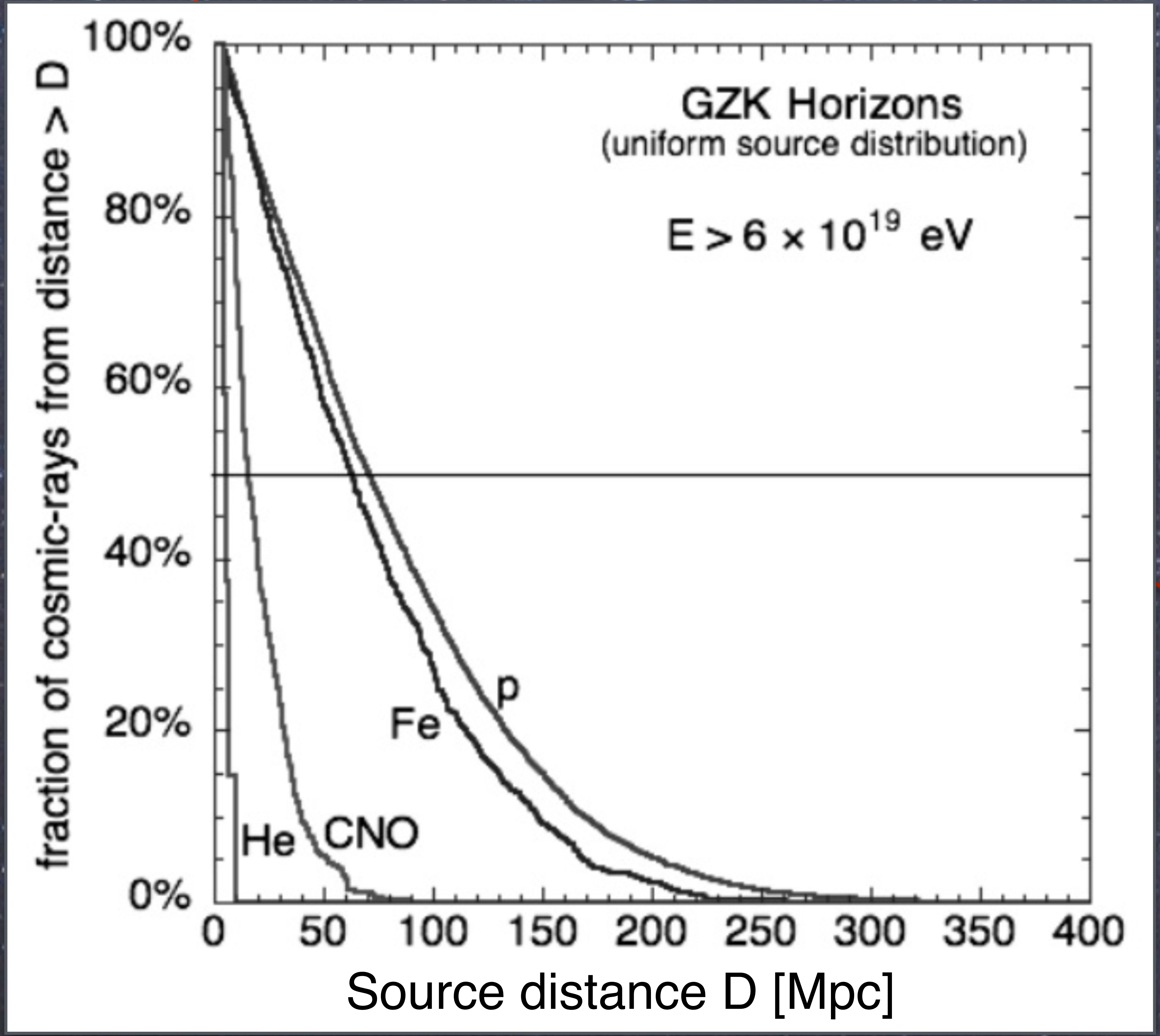
PDG, Chin.Phys. C38 (2014) 090001

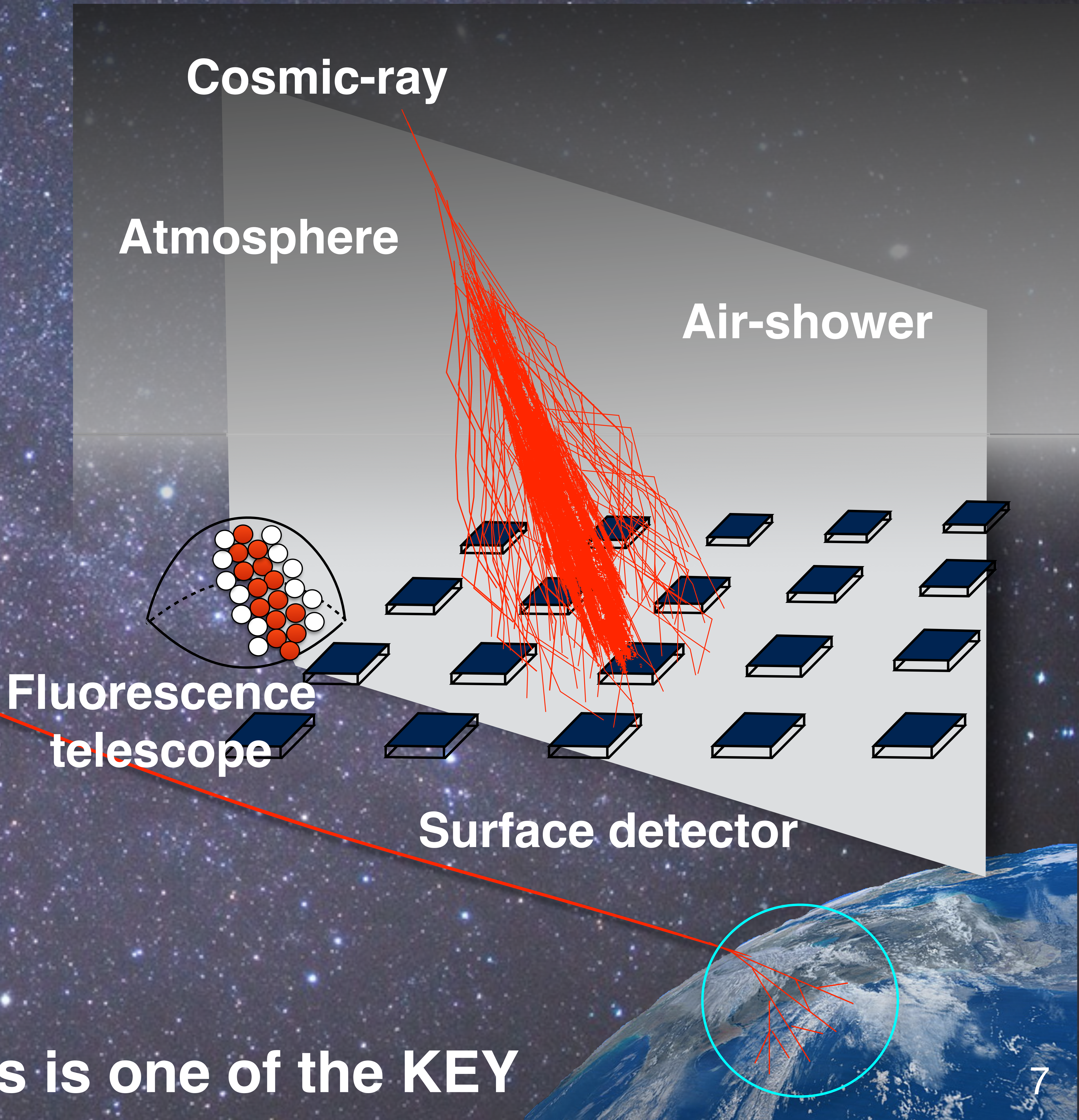
Galactic field is too weak to contain UHECRs —> extra-galactic

What is the origin of UHECR

Source candidates:
- ✦Active Galactic Nuclei (AGNs)
- ✦Gamma Ray Burst (GRBs)
- ✦. . .

arXiv: 0911.4714

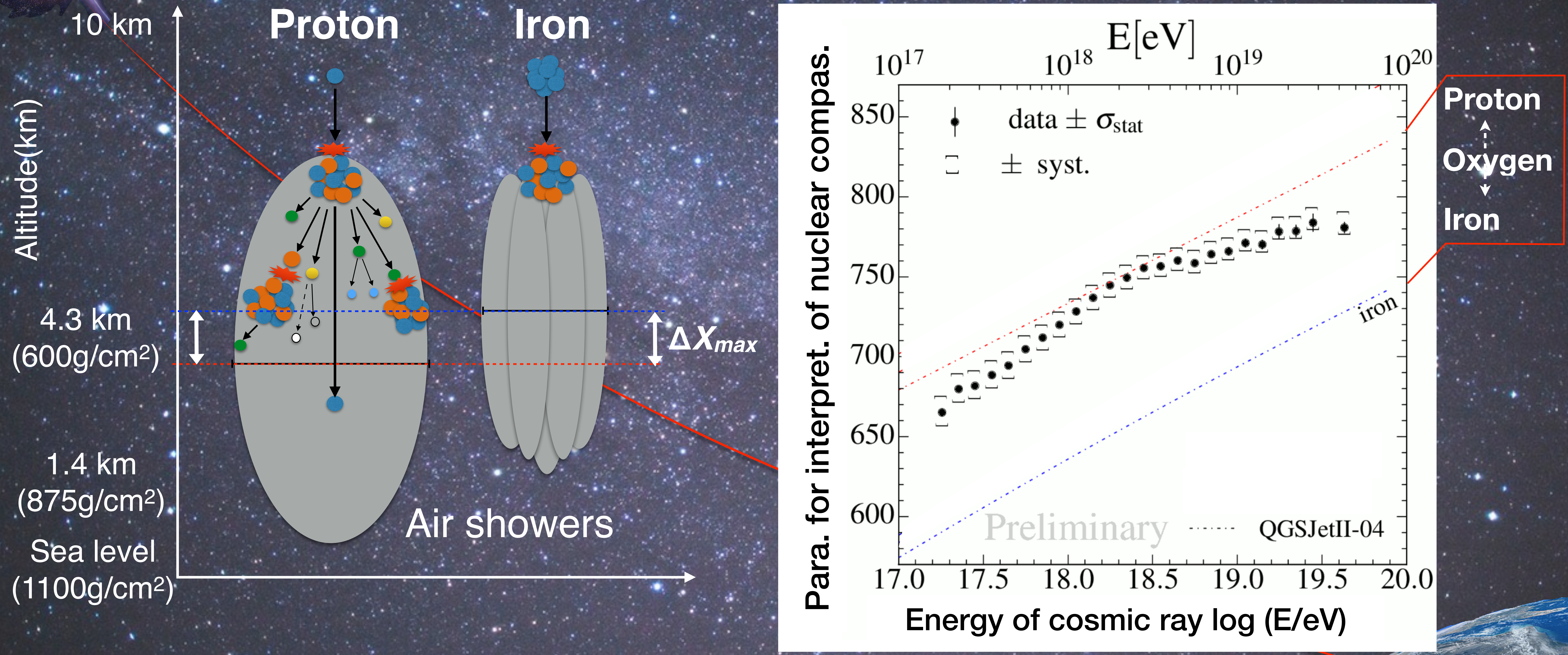




Nuclear composition of UHECRs is one of the KEY

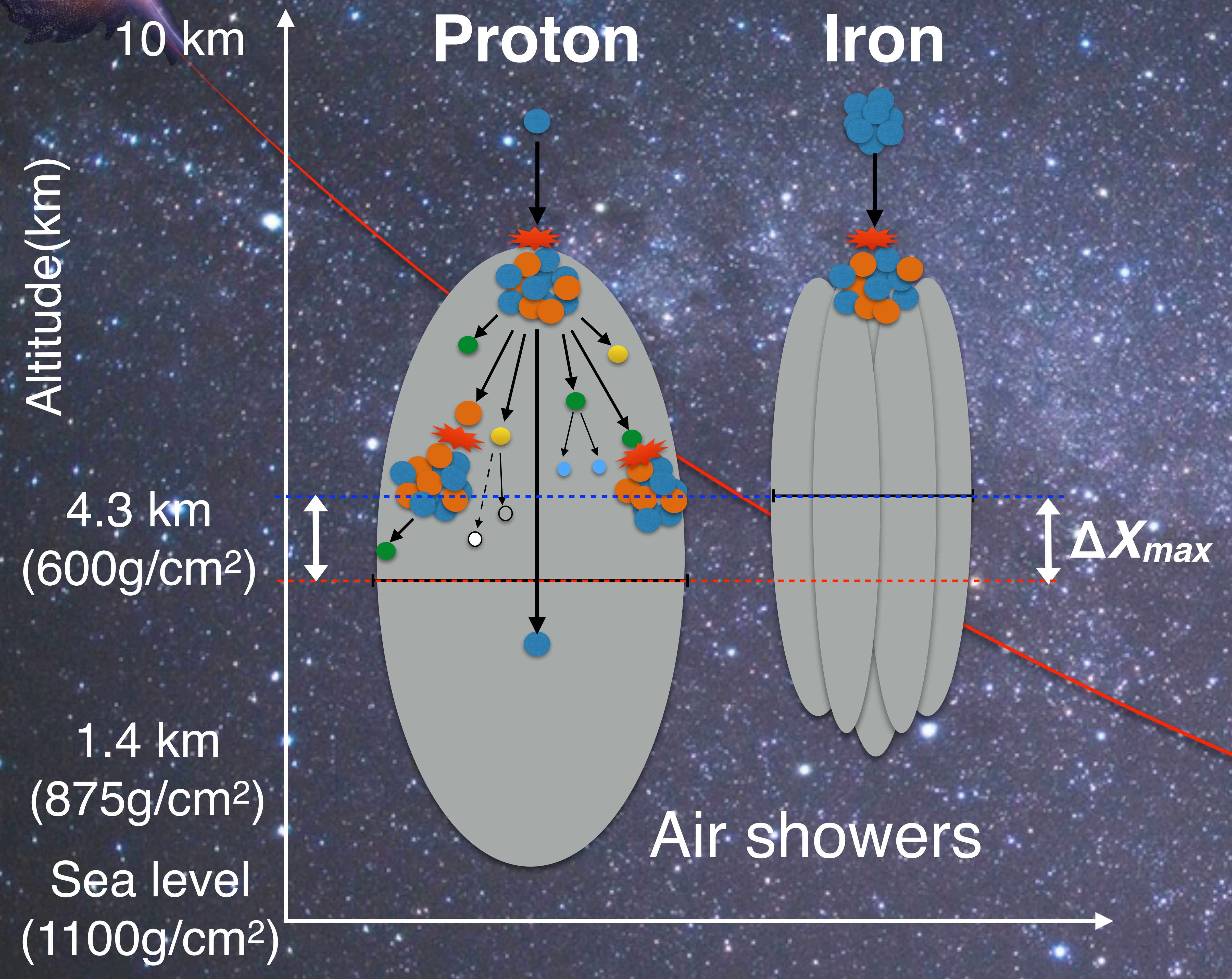
How to interpret the observable

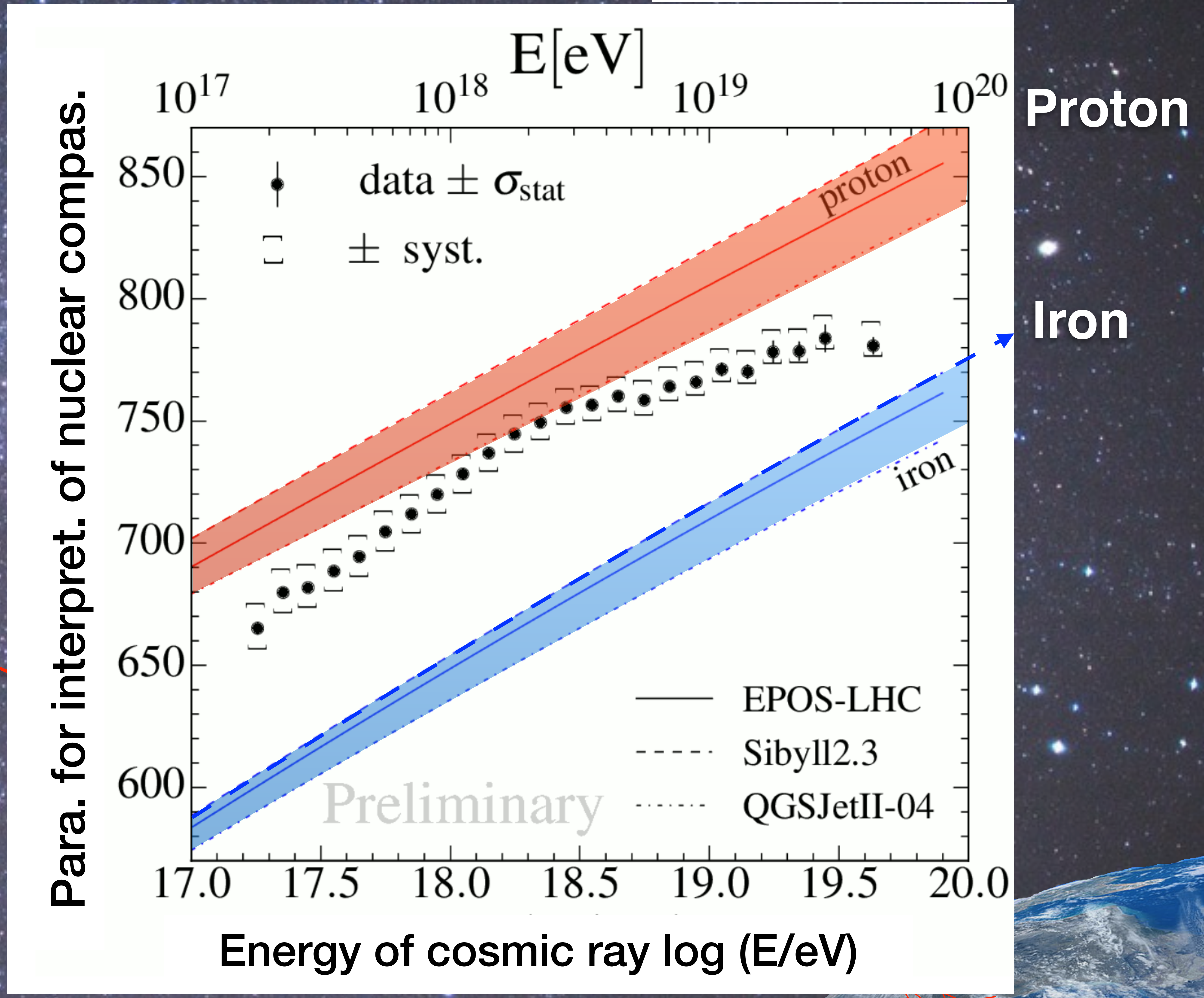
arXiv: 1708.06592



How to interpret the observable

arXiv: 1708.06592

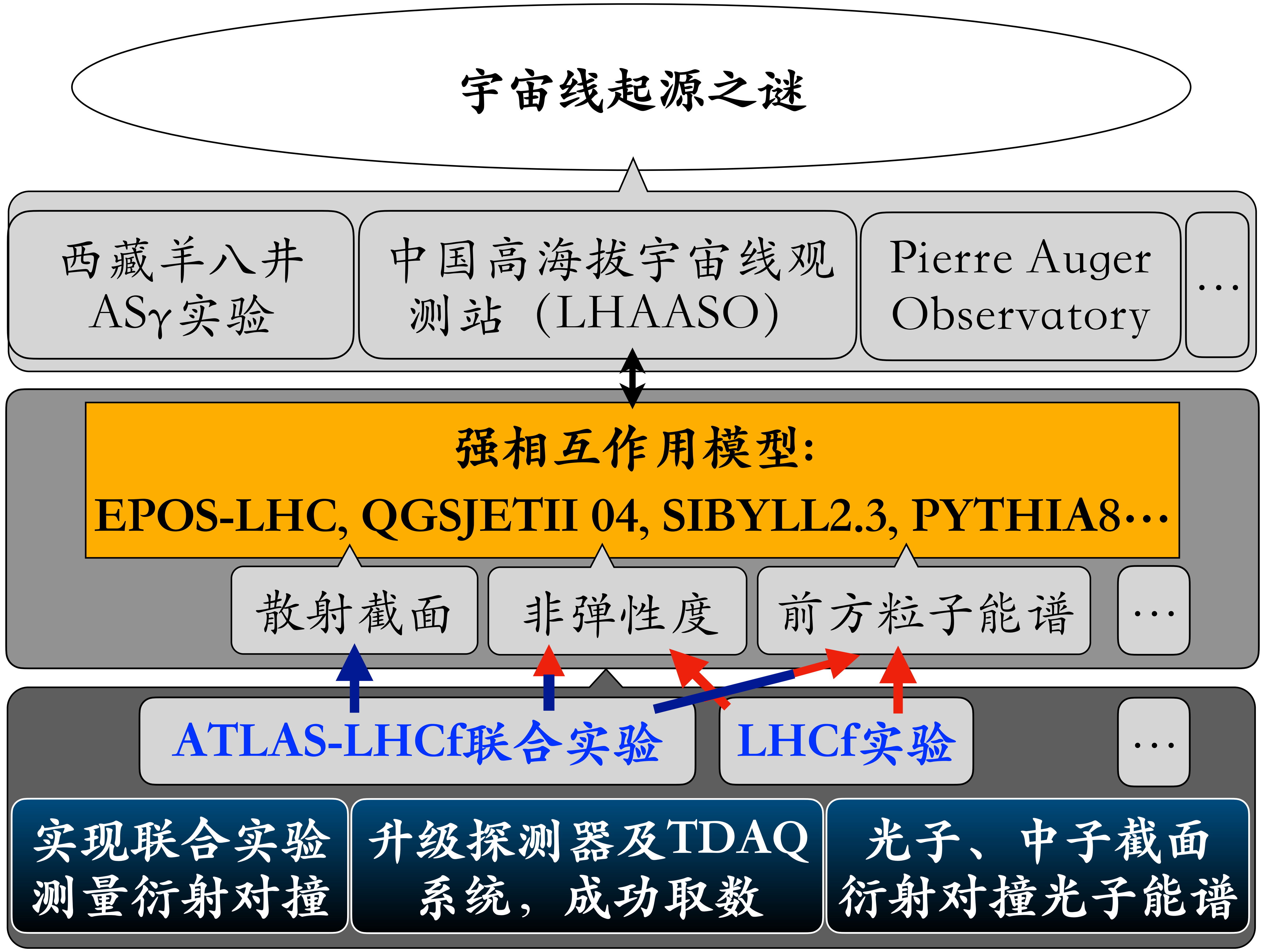




The issue to interpret the air shower data:

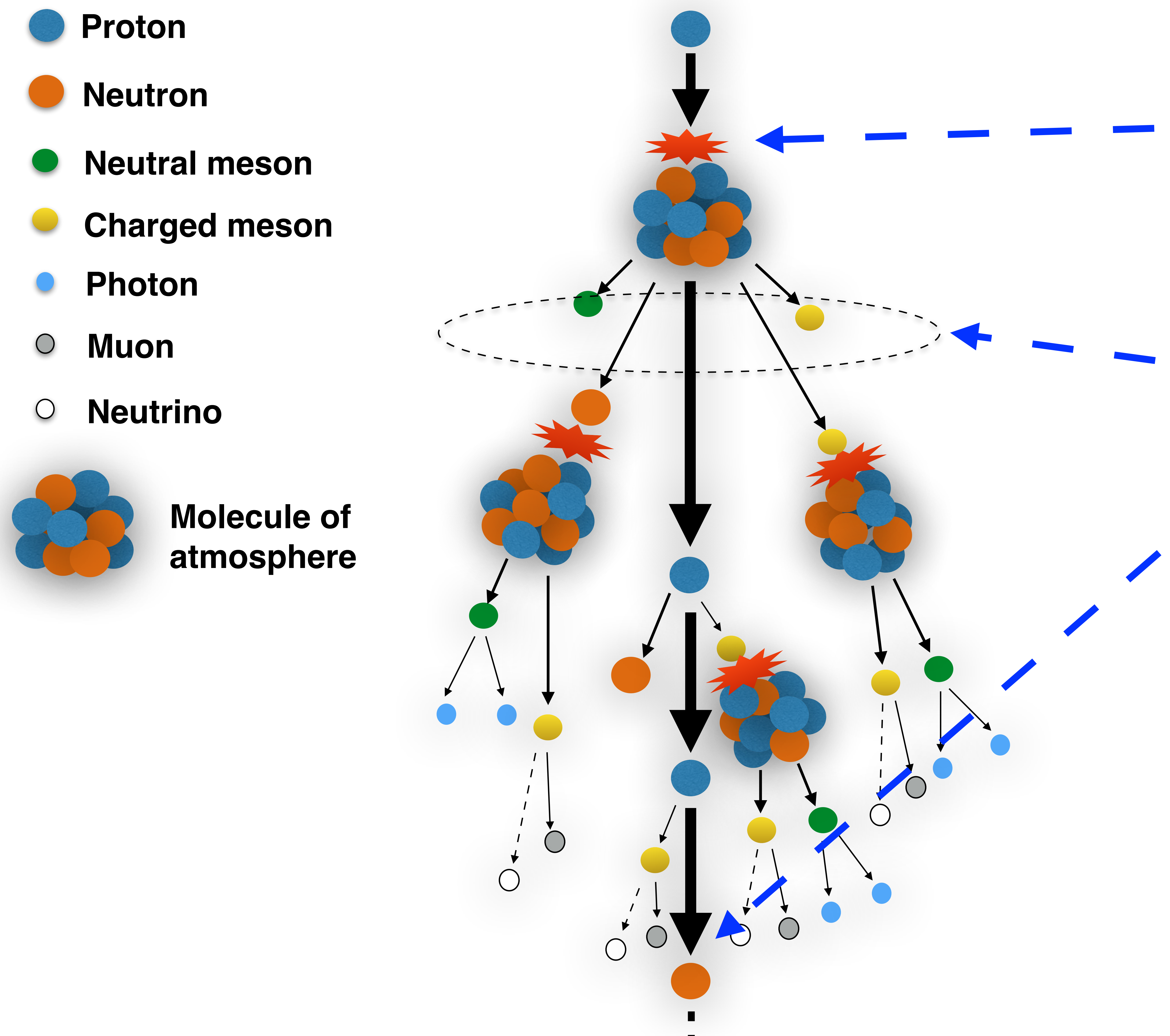
- Largely unknown model uncertainties
- Limitations in modeling of hadronic interactions in air shower (soft processes)

Hadronic interaction models



What to be calibrated by accelerators

- Hard interactions can be predicted by using perturbative QCD.
- Soft interactions dominate by non-perturbative QCD,
  ➡Phenomenological models base on Regge theory proposed.



<u>Key parameters</u>

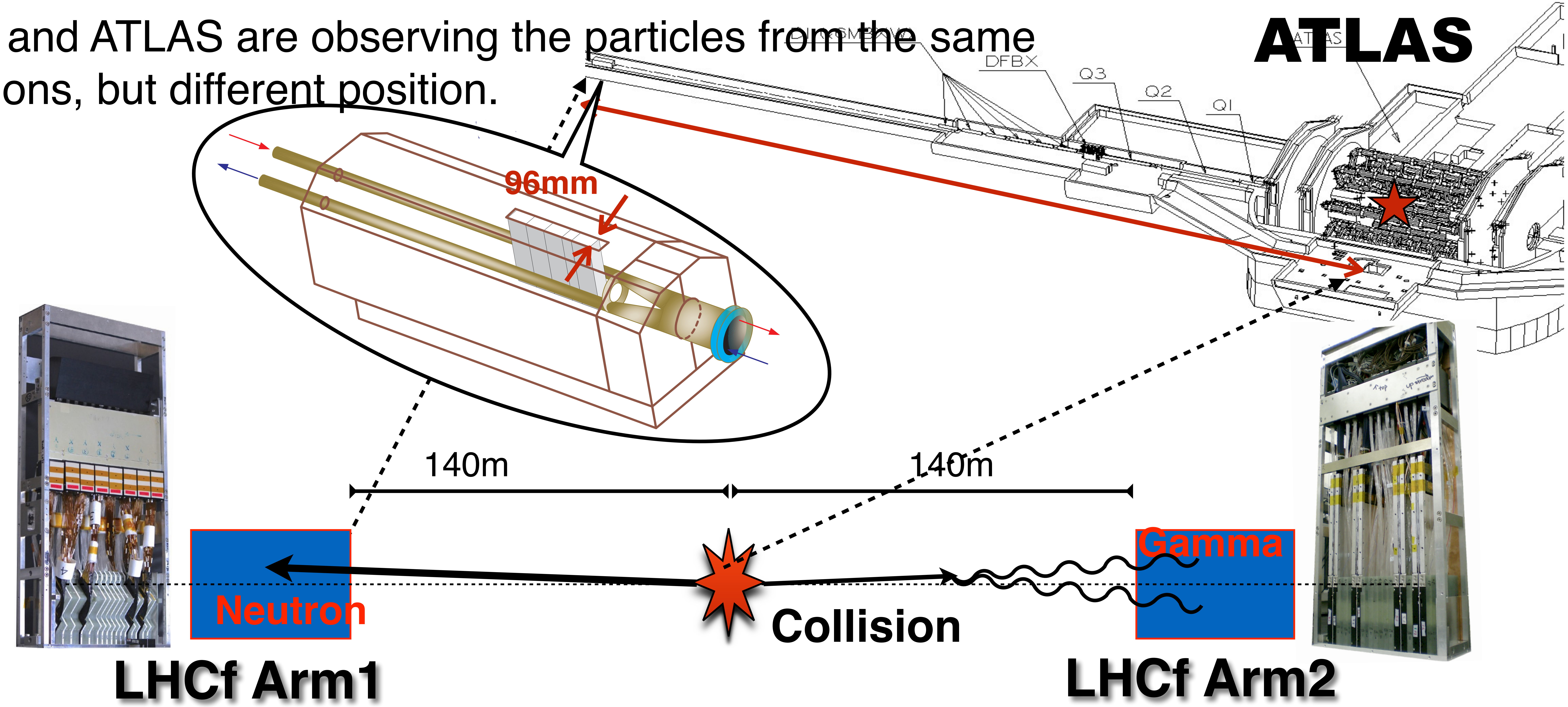
- Inelastic cross section (interaction mean free path)
  TOTEM, ATLAS, CMS, etc.
- Multiplicity
  Central detector
- Inelasticity ($\kappa_{inela} = 1 - P_{lead}/P_{beam}$)
  LHCf, etc.

arXiv:1307.7131v1

Property Increased	Change in X_{max}
Cross section	Decreased
Inelasticity	Decreased
Multiplicity	Decreased

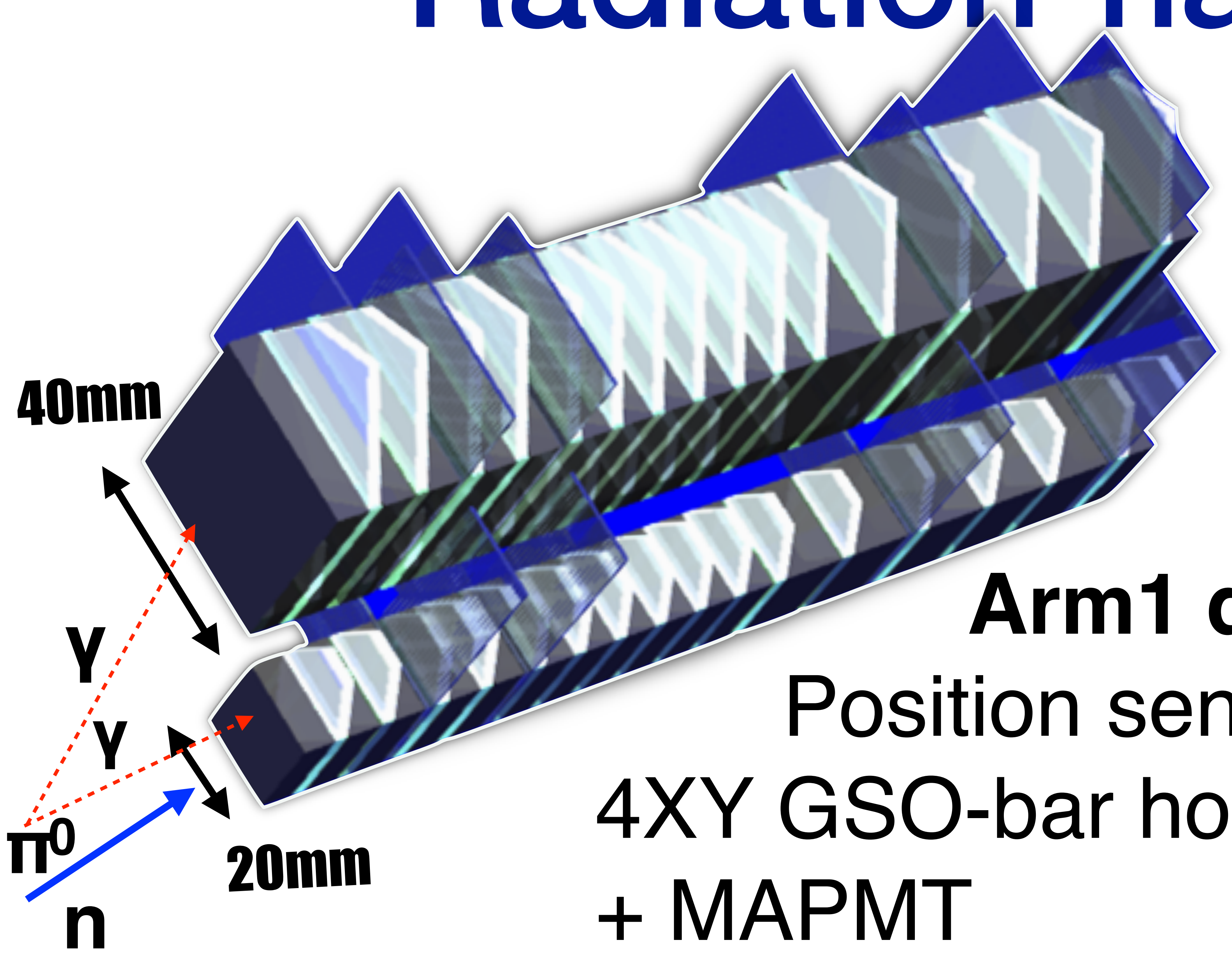
The LHCf experiment

- Measuring hadronic production cross section of neutral particles emitted in the very forward region of LHC.
- LHCf and ATLAS are observing the particles from the same collisions, but different position.



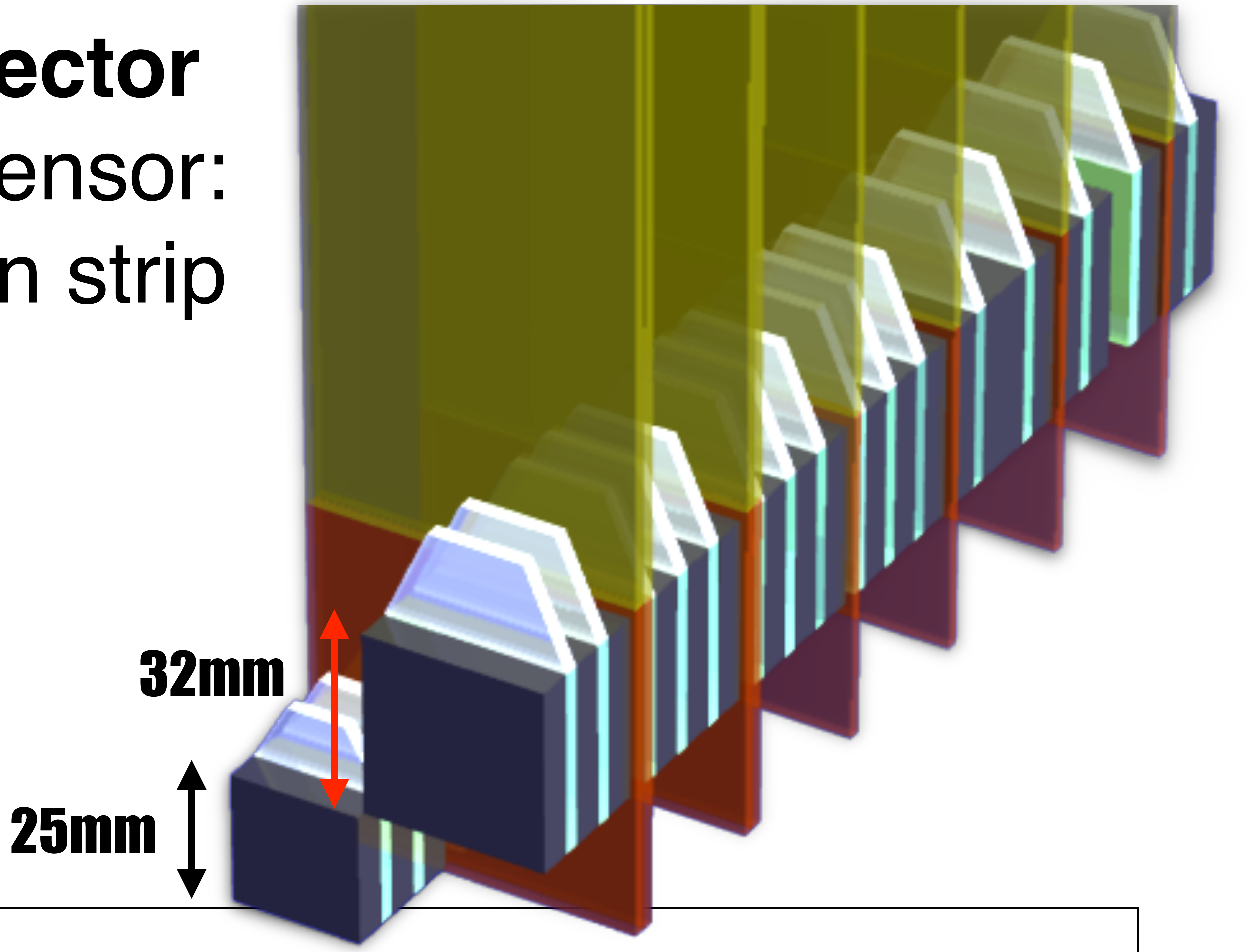
LHCf detectors are sensitive to the ***Low-mass diffraction***

Radiation-hard calorimeter performance



Arm1 detector
Position sensor:
4XY GSO-bar hodoscope
+ MAPMT

Arm2 detector
Position sensor:
4XY silicon strip
detectors



- Two imaging sampling shower calorimeters
- 44r.l. tungsten, 16 layers of GSO scintillators and 4 position sensitive layers
- The η coverage of the calorimeter: $|\eta|>8.4$

Performance

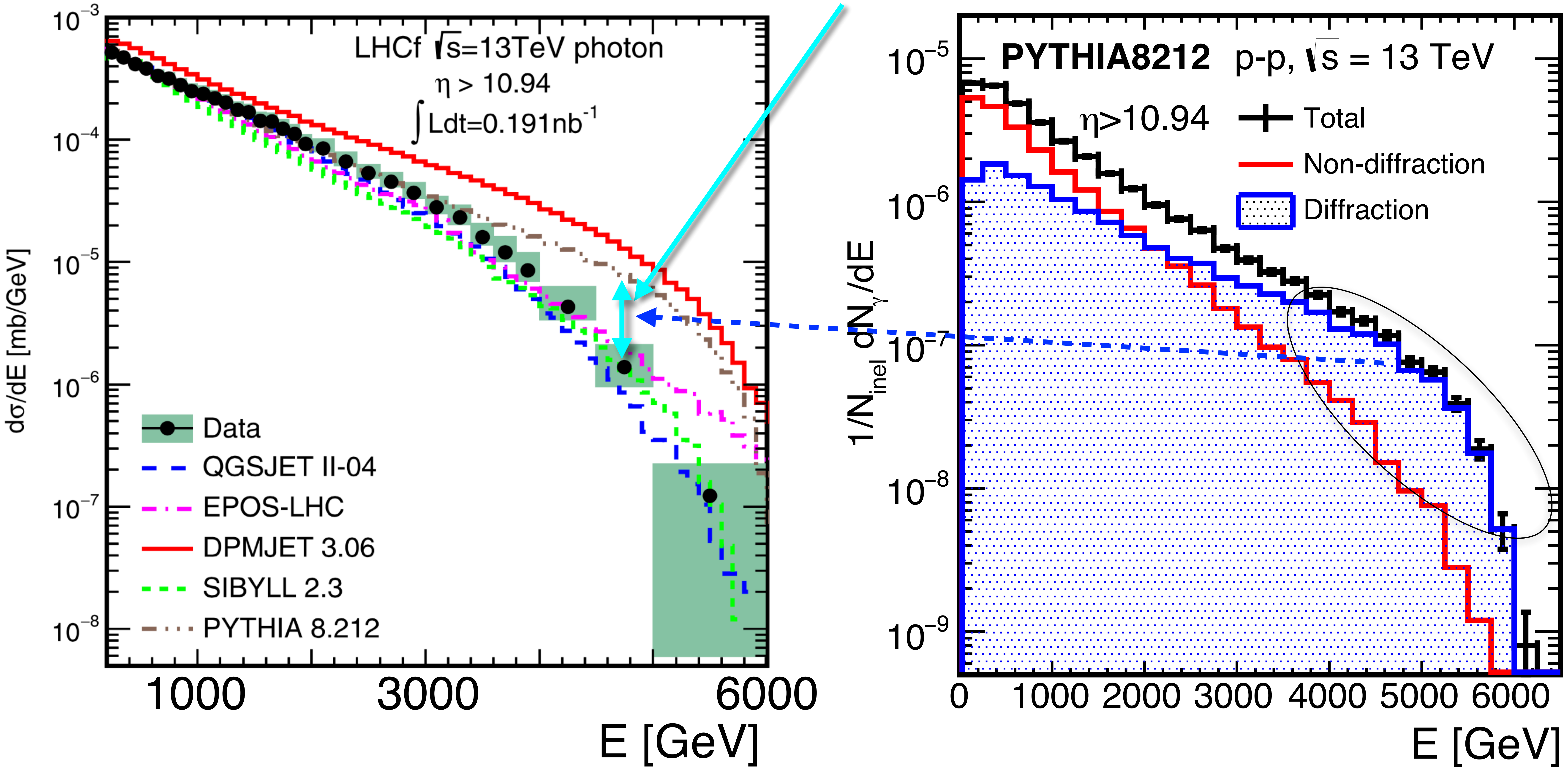
Energy resolution:(>100GeV)		Position resolution:	
<5%	for photons	<200μm	for photons
40%	for neutrons	<1mm	for neutrons

Forward photon spectra from low-mass diff.

- Forward photon production at √s = 13 TeV in p-p collisions has been measured by LHCf.

Large descripency between data and PYTHIA8

PLB 780, (2018) 233-239

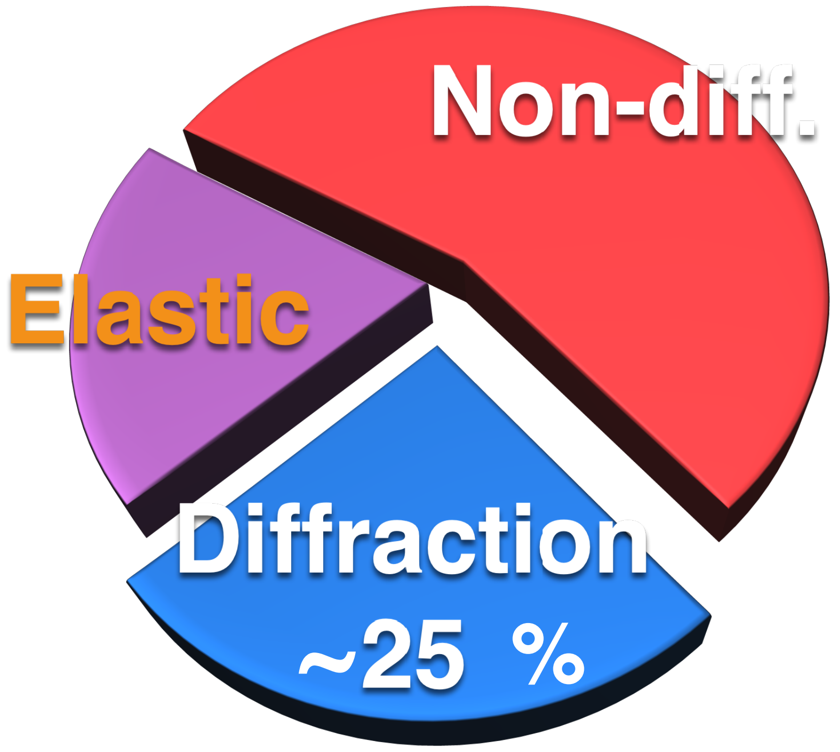


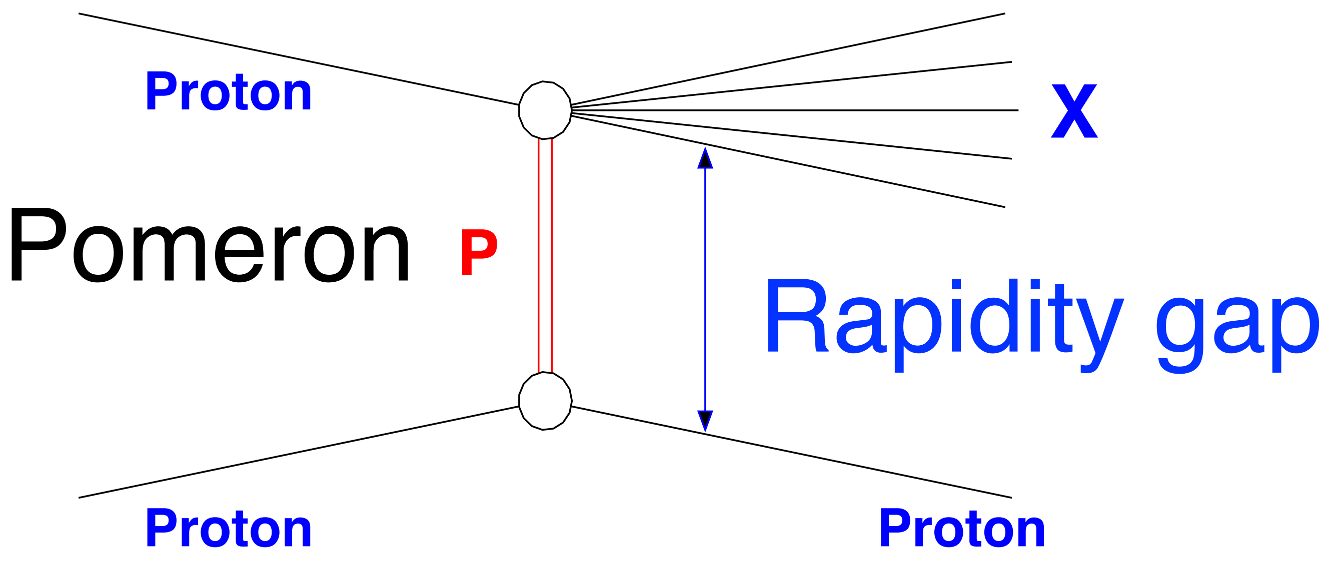
EPJ. C77 (2017) 212

- Discrepancies between data and model predictions for the forward photon spectra in pp √s = 13 TeV collisions.
- The excess of PYTHIA8 at E>3TeV was assumed due to over contribution from low-mass diff. processes.

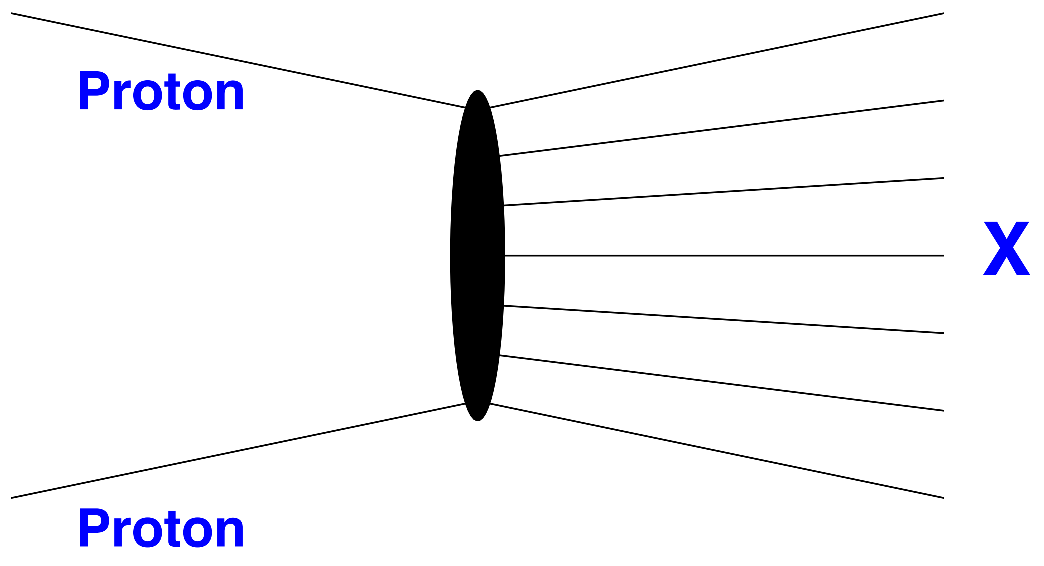
Diffraction vs. air-shower developments

- LHCf has verified the hadronic interactions inclusively.
- This research measured **diffractive processes exclusively**, which are less constraint in the model and have big impact to the air-shower development.

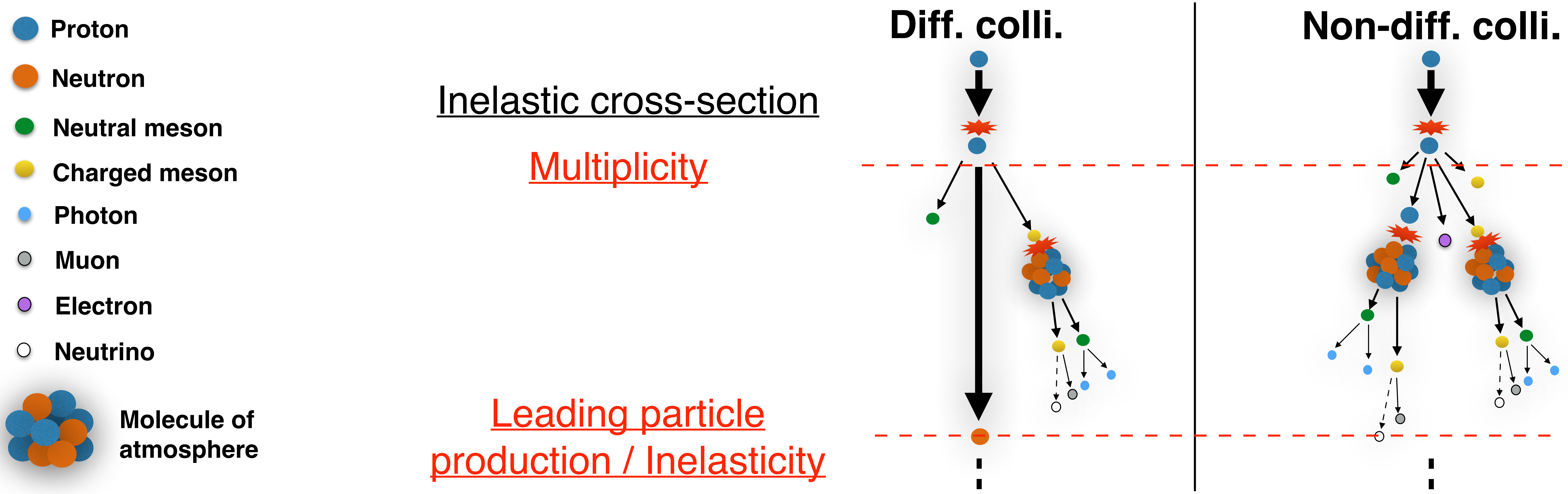




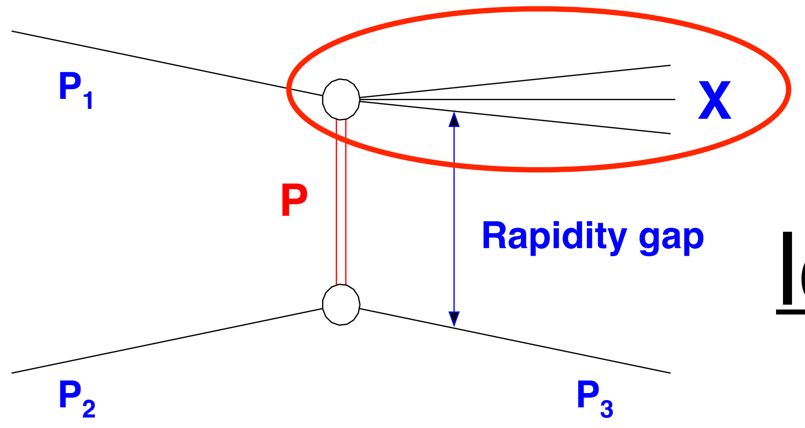
Single diffraction



Non diffraction

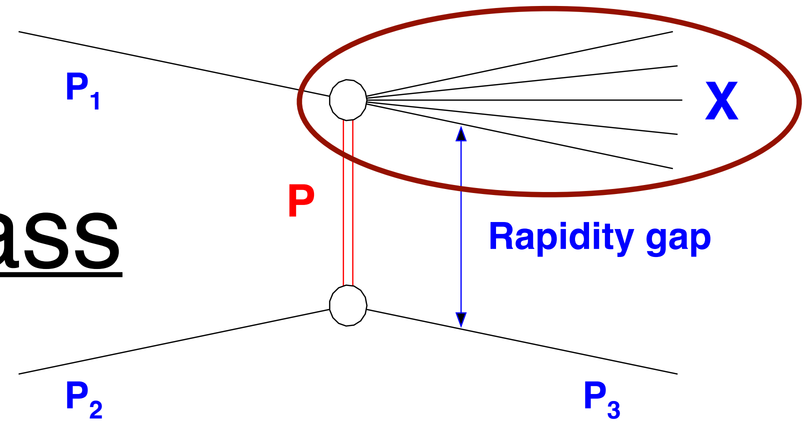


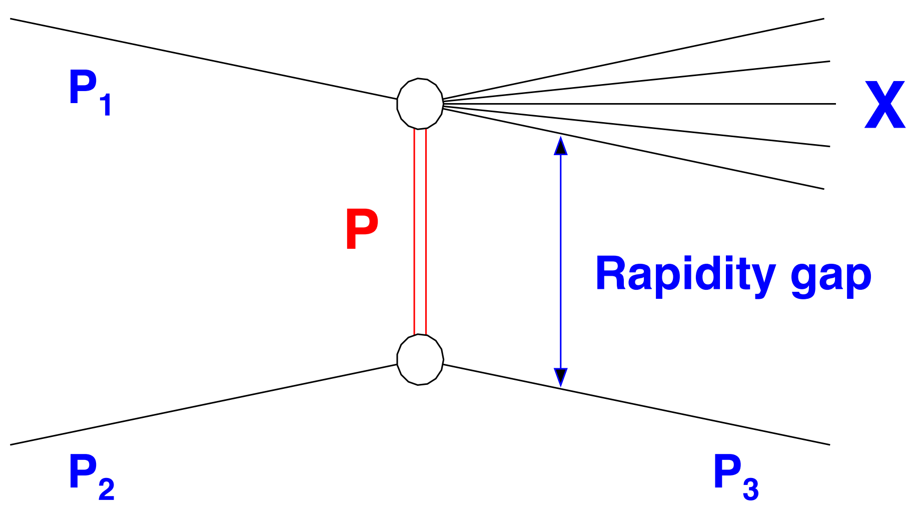
Objective and originality



low-mass

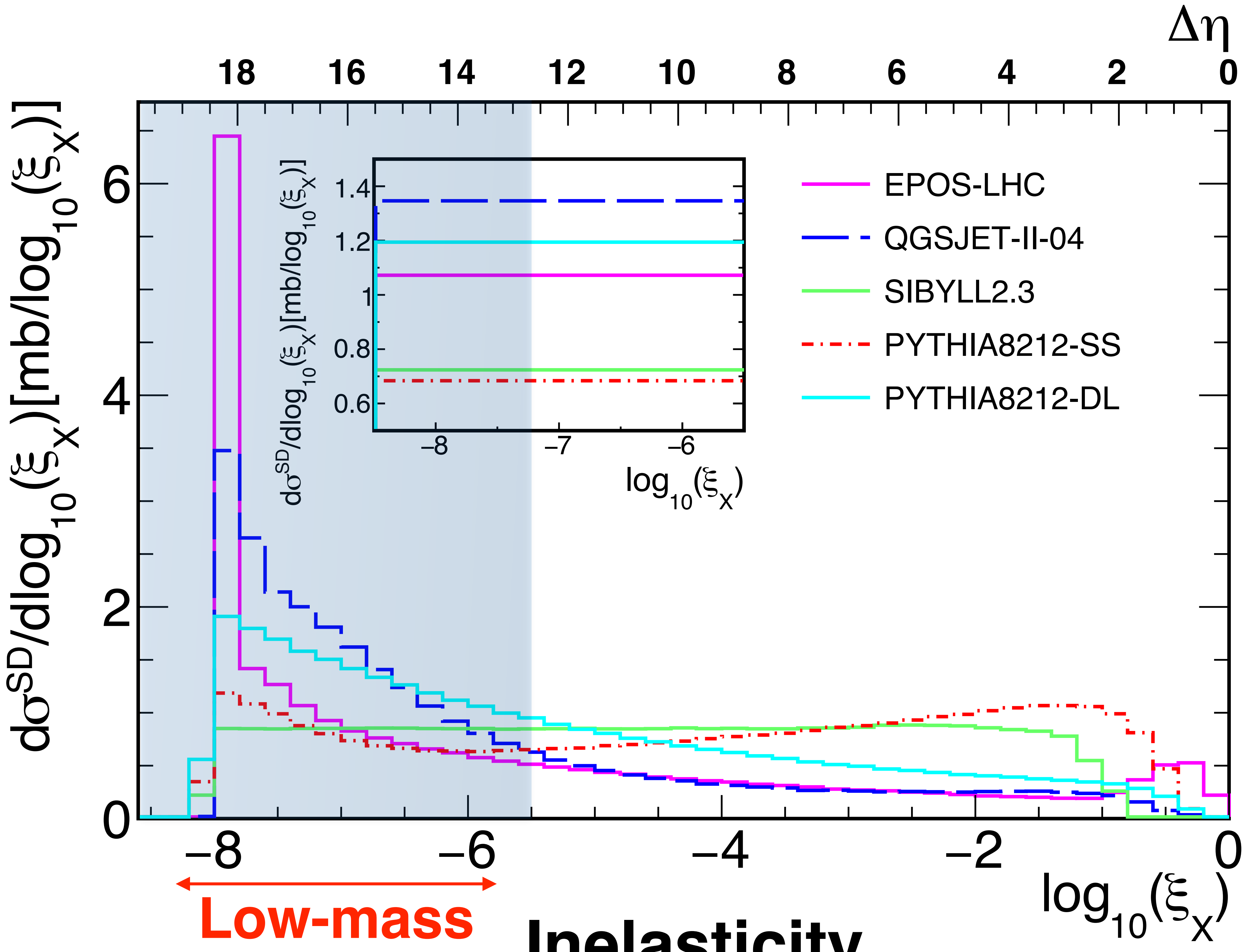
high-mass





M_X : Diffractive mass, invariant mass of dissociated system

$$\xi_X = \left(\frac{M_X}{\sqrt{s}}\right)^2 \simeq e^{-\Delta\eta}$$



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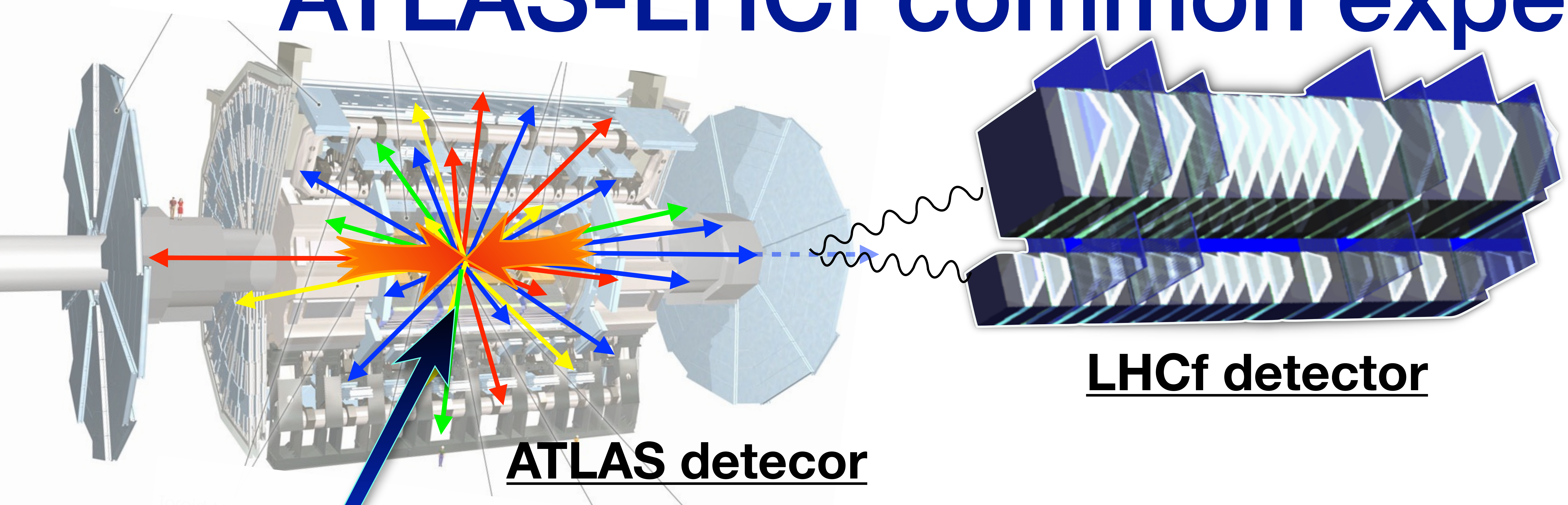
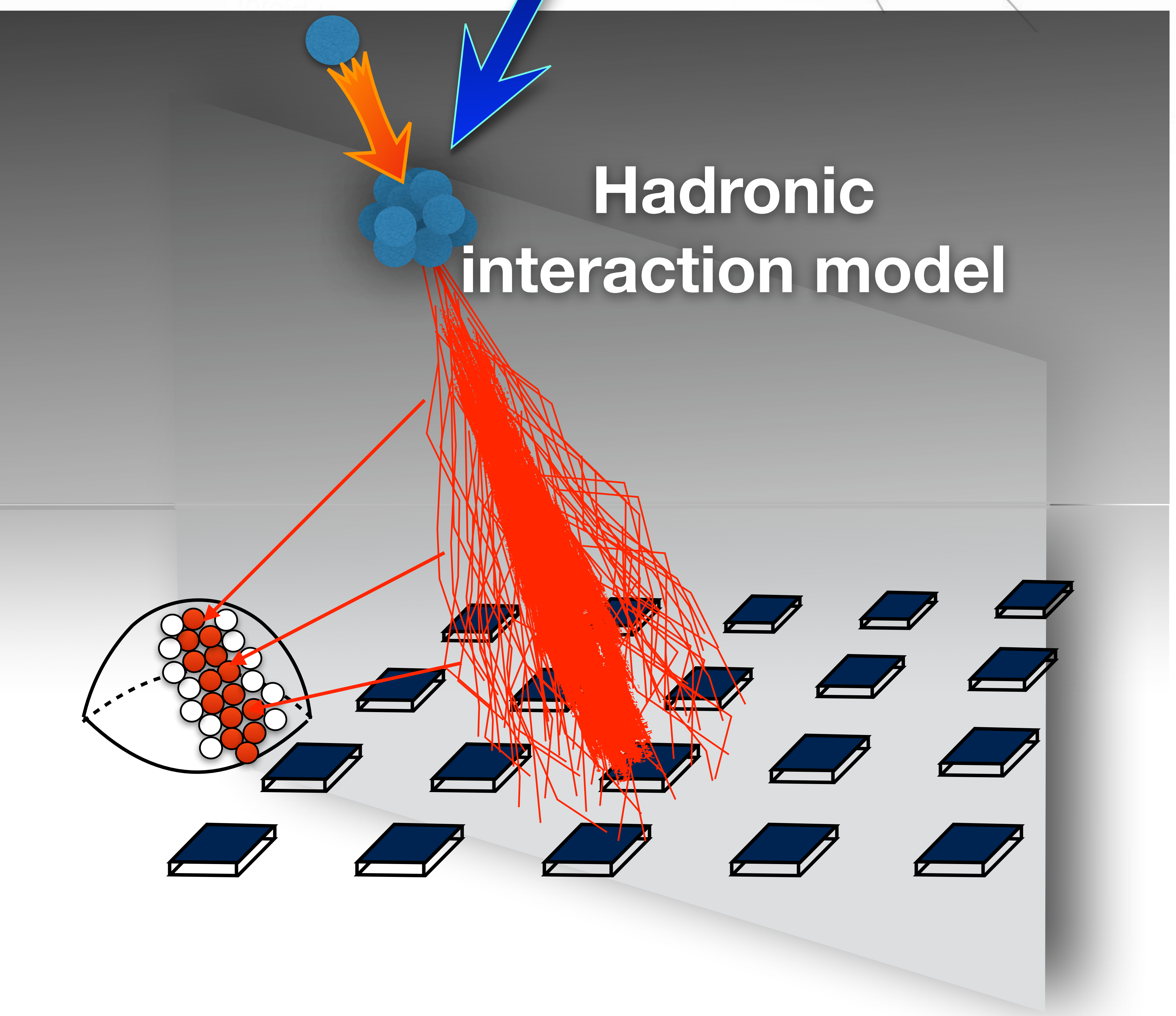
Inelasticity

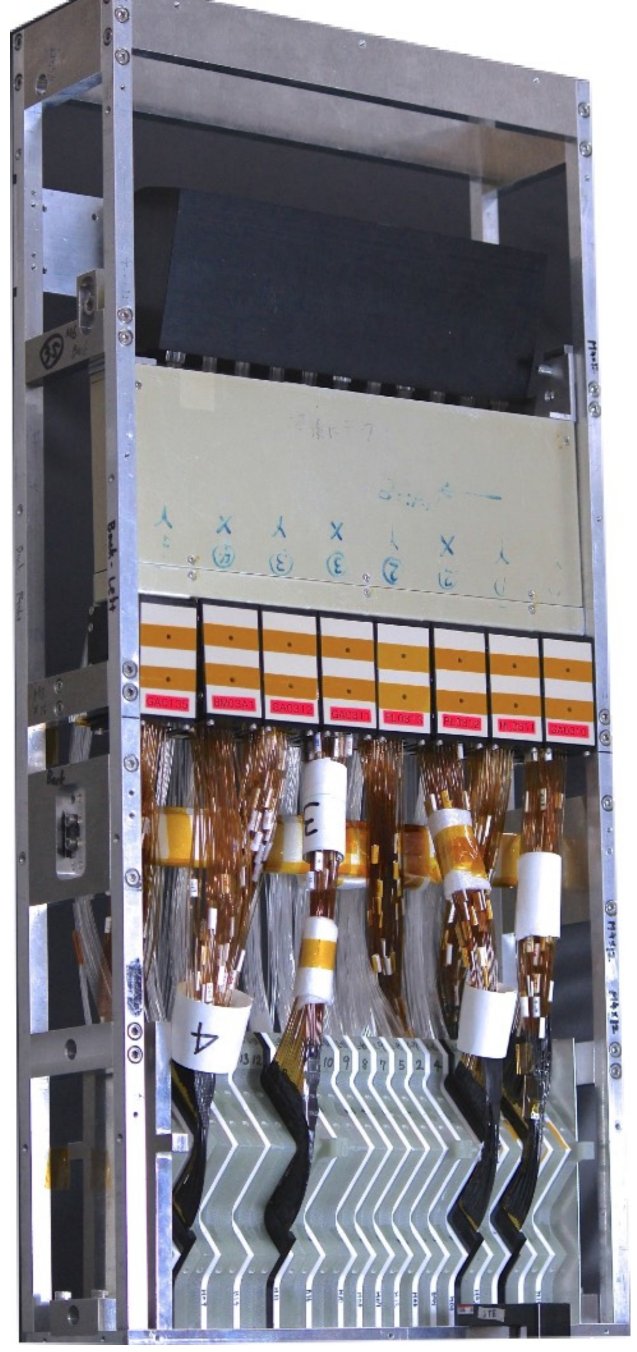
small **large**

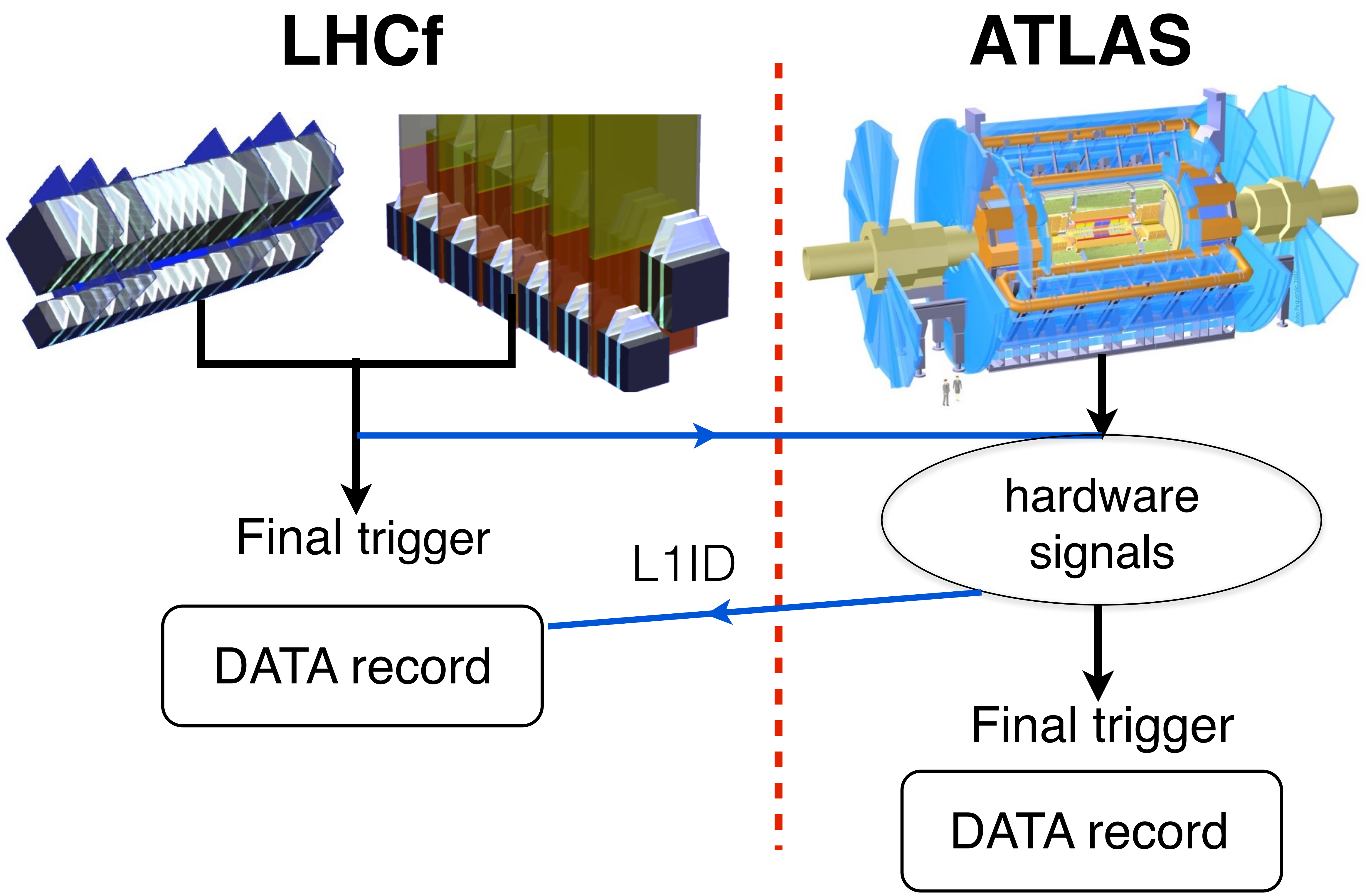
Large discrepancy exists among models, especially, at low mass.

ATLAS-LHCf common experiment

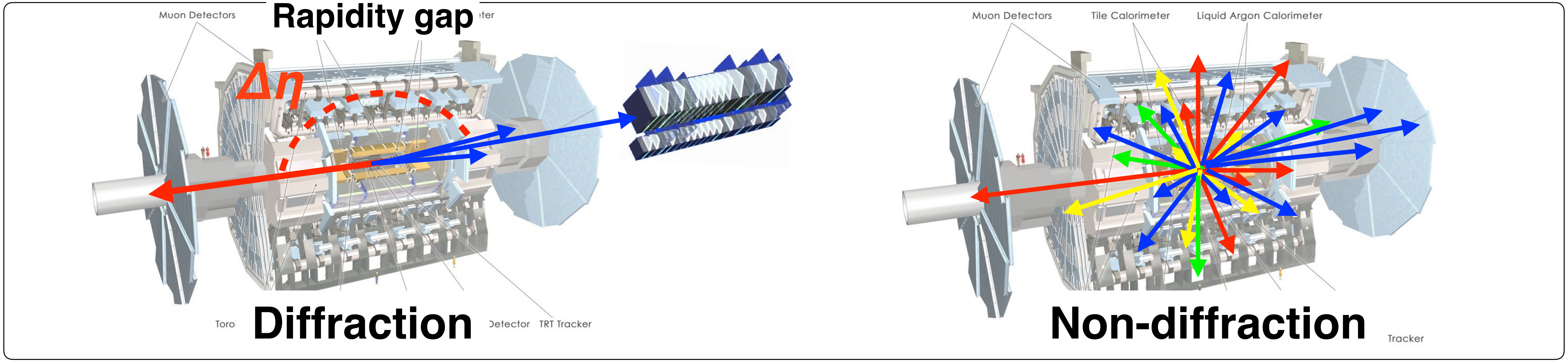


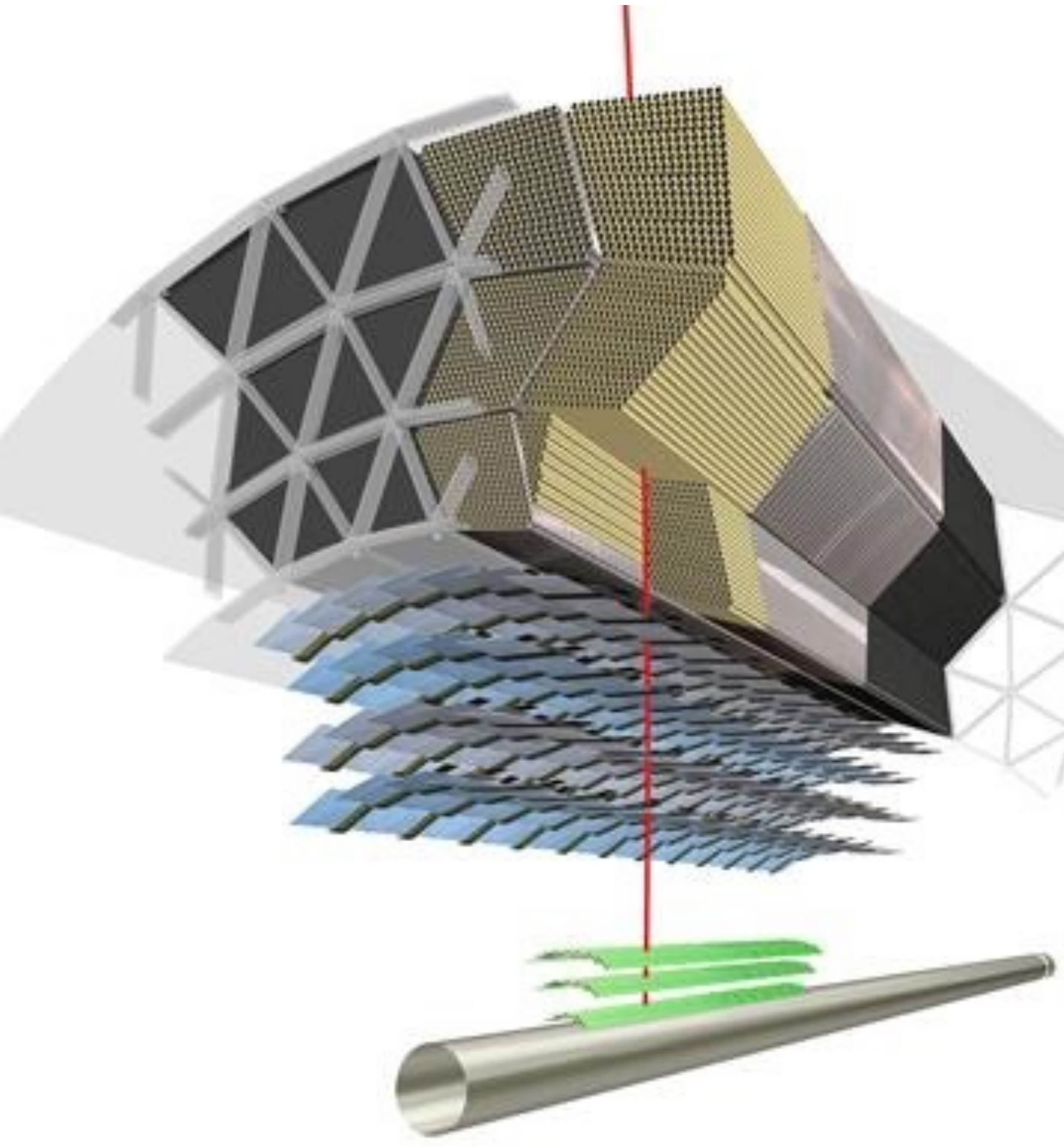




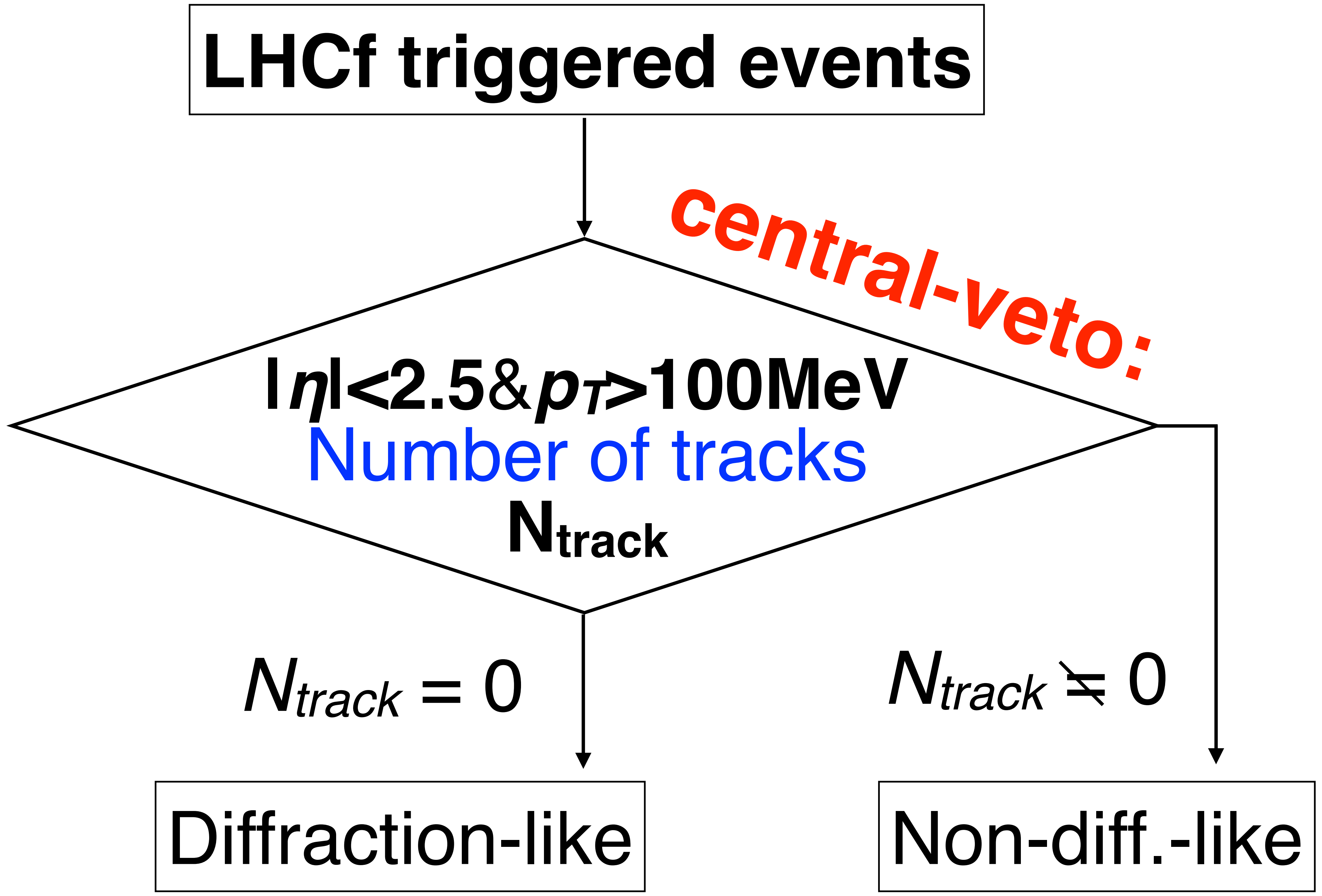


Diffraction identification by central-veto

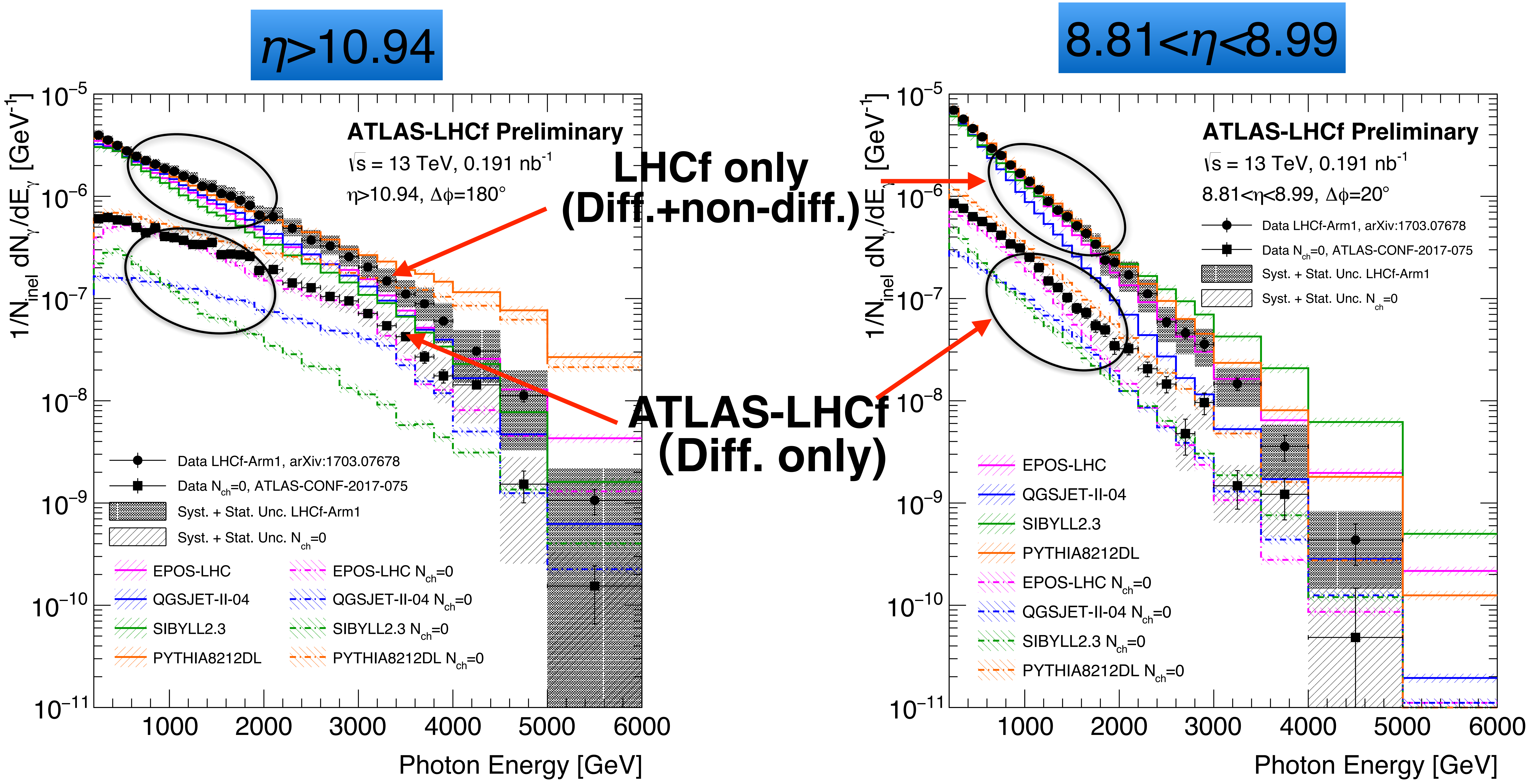




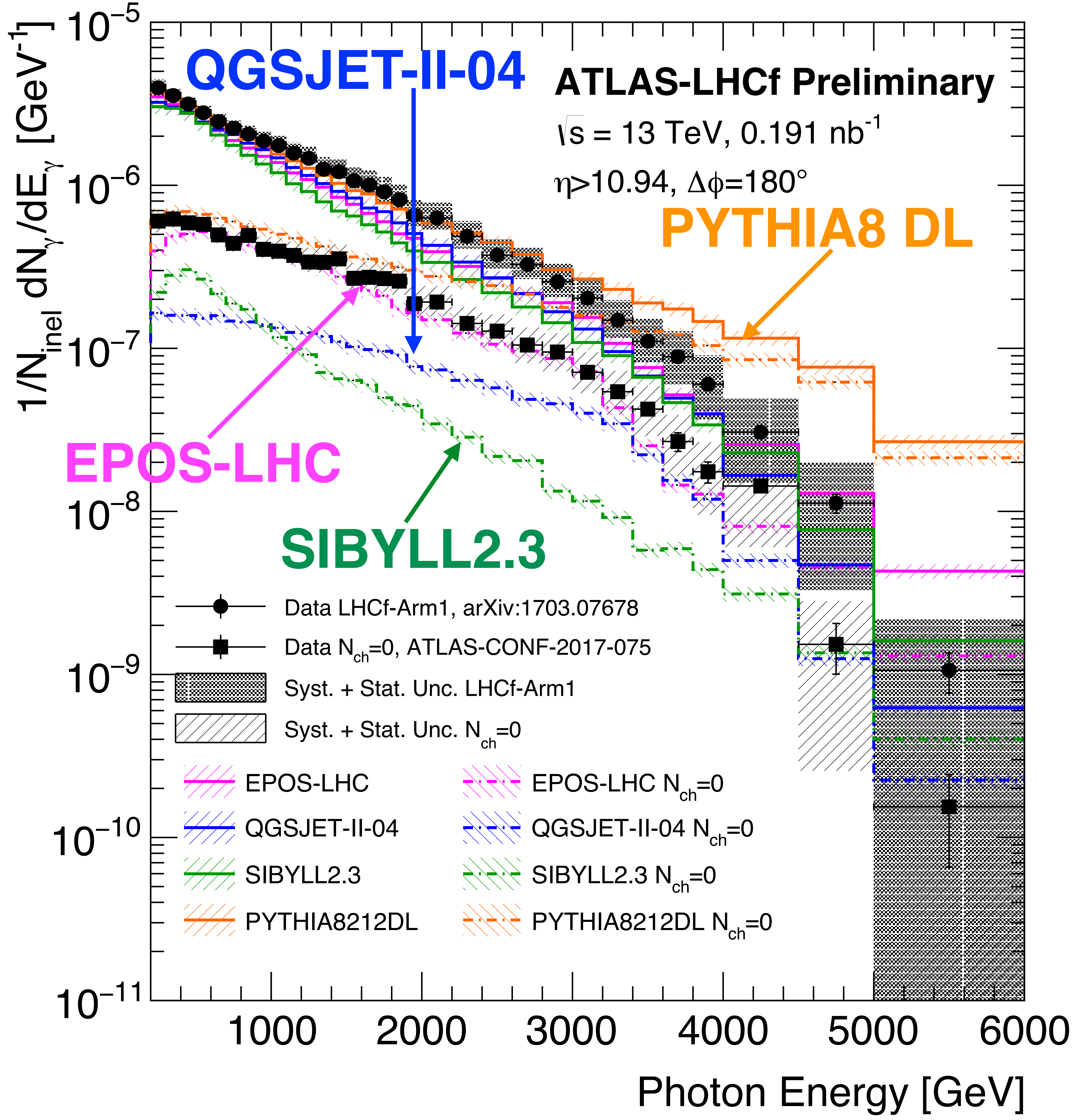
- Rapidity gap measured by ATLAS to distinguish the events triggered by LHCf to diff.-like and non-diff.-like
- First direct measurement of low-mass diffraction at high energies.



Results: Photon spectra



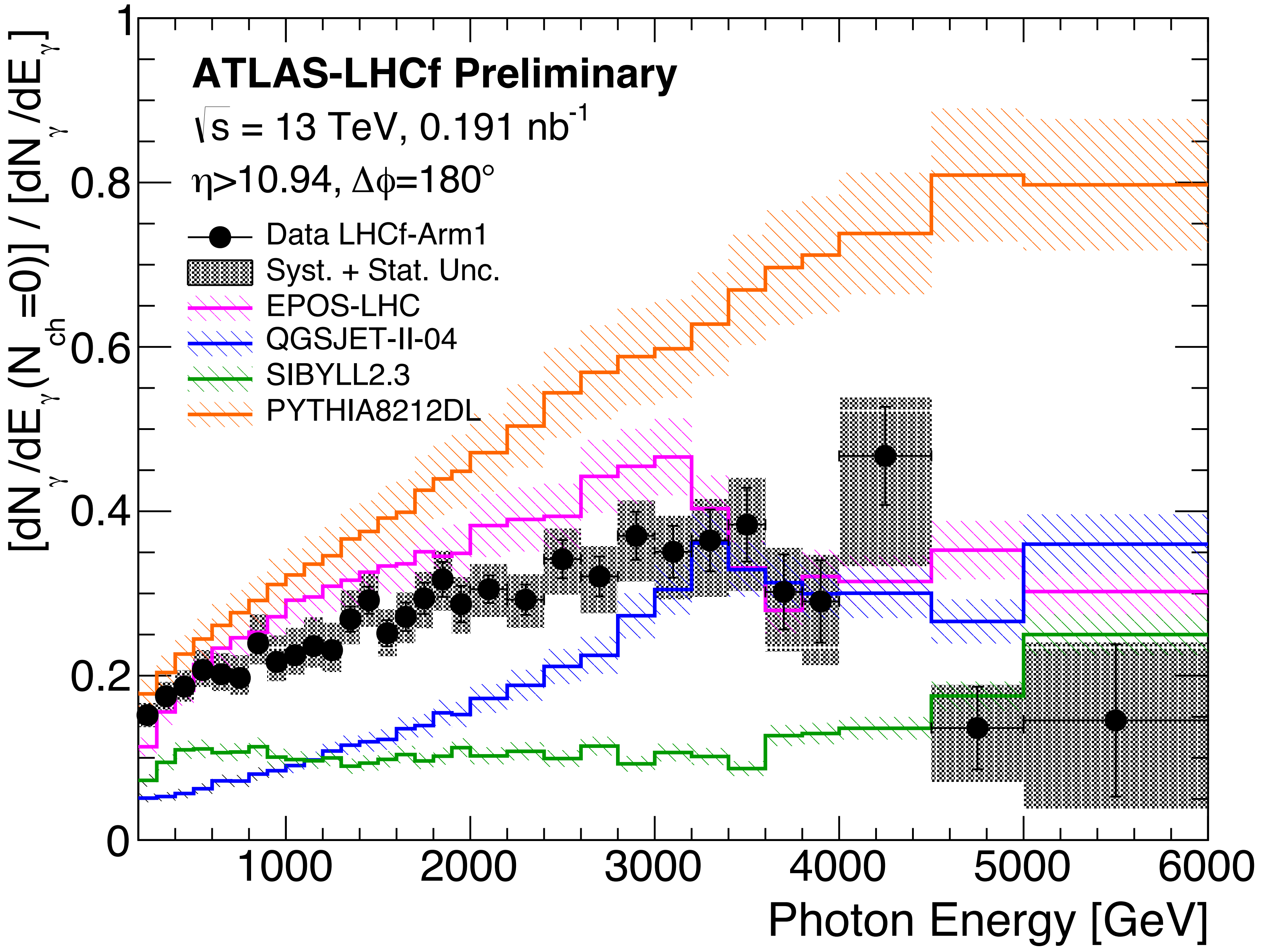
- ✦ Comparison between data w/ N_{ch} = 0 and model predictions
  - EPOS-LHC show a good agreement with data at $\eta > 10.94$.
  - PYTHIA8212DL show a good agreement at the region of $8.81 < \eta < 8.99$.



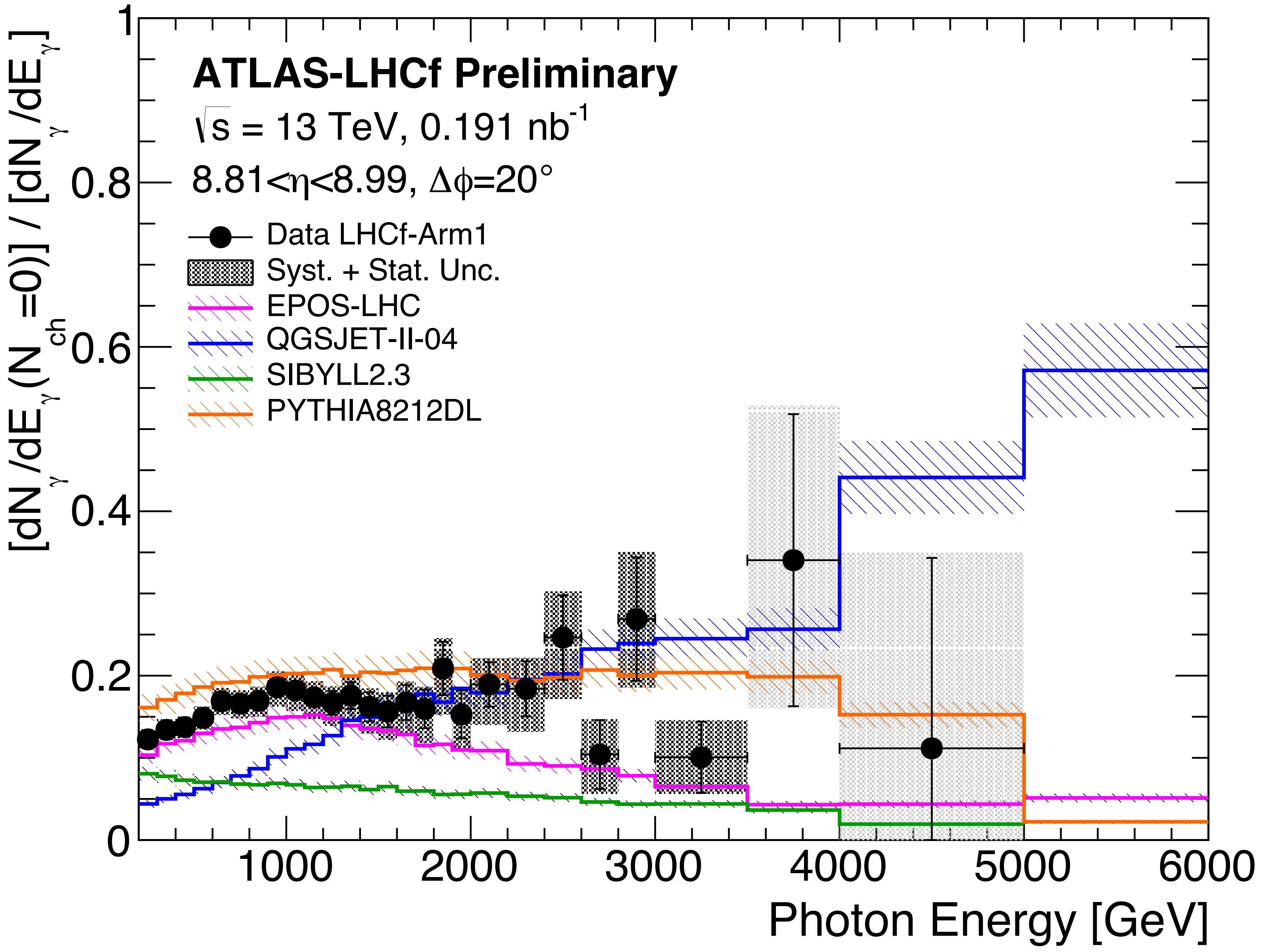
QGSJET-II-04
ATLAS-LHCf Preliminary
√s = 13 TeV, 0.191 nb^{-1}
η>10.94, Δφ=180°
PYTHIA8 DL
EPOS-LHC
SIBYLL2.3
Data LHCf-Arm1, arXiv:1703.07678
Data N_{ch}=0, ATLAS-CONF-2017-075
Syst. + Stat. Unc. LHCf-Arm1
Syst. + Stat. Unc. N_{ch}=0
EPOS-LHC
EPOS-LHC N_{ch}=0
QGSJET-II-04
QGSJET-II-04 N_{ch}=0
SIBYLL2.3
SIBYLL2.3 N_{ch}=0
PYTHIA8212DL
PYTHIA8212DL N_{ch}=0
$1/N_{inel}\, dN_\gamma/dE_\gamma$ [GeV^{-1}]
Photon Energy [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1000
2000
3000
4000
5000
6000

Results: Spectra ratios $N'_{ch=0}(E)$ / $N'_{ALL}(E)$

η>10.94

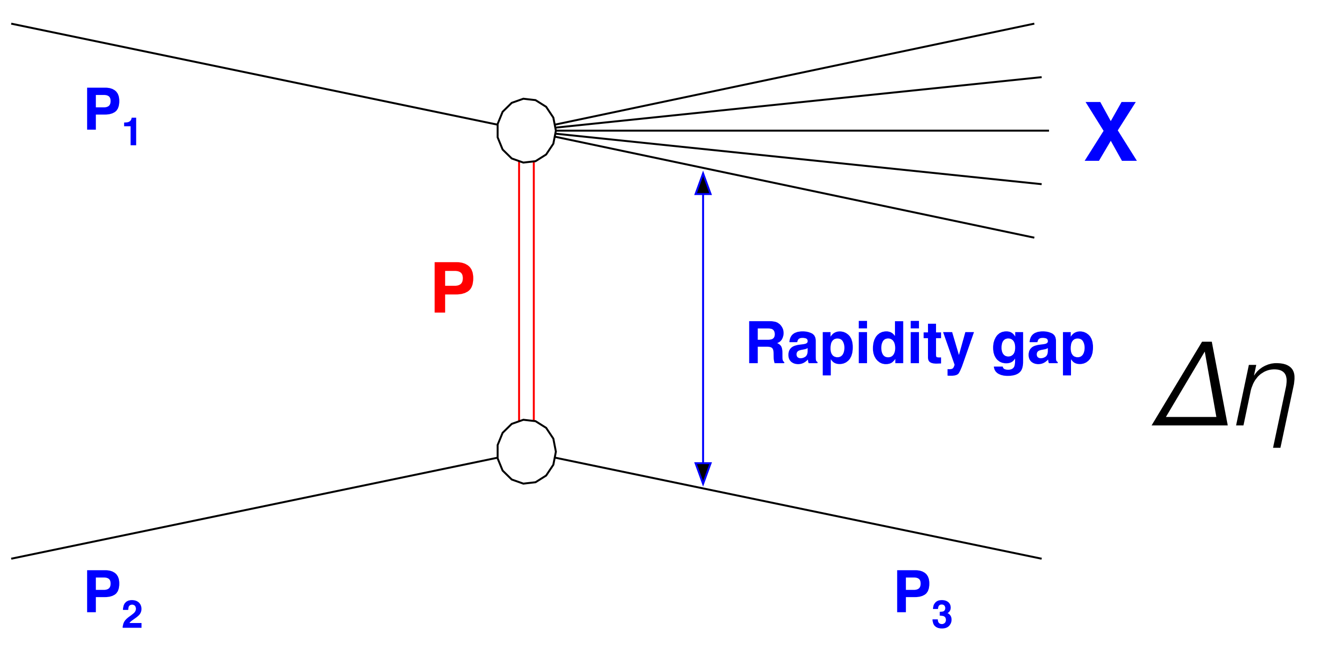


8.81<η<8.99



- At η>10.94, the ratio of data increased from 0.15 to 0.4 with increasing of the photon energy up to 4TeV.
  - PYTHIA8212DL predicts higher fraction at higher energies.
  - SIBYLL2.3 show small fraction compare with data.
- At $8.81 < \eta < 8.99$, the ratio of data keep almost constant as 0.17.
  - EPOS-LHC and PYTHIA8212DL show good agreement with data at $8.81 < \eta < 8.99$.

Tuning of pomeron flux



$\Delta\eta$

M_X : Diffractive mass, invariant mass of dissociated system

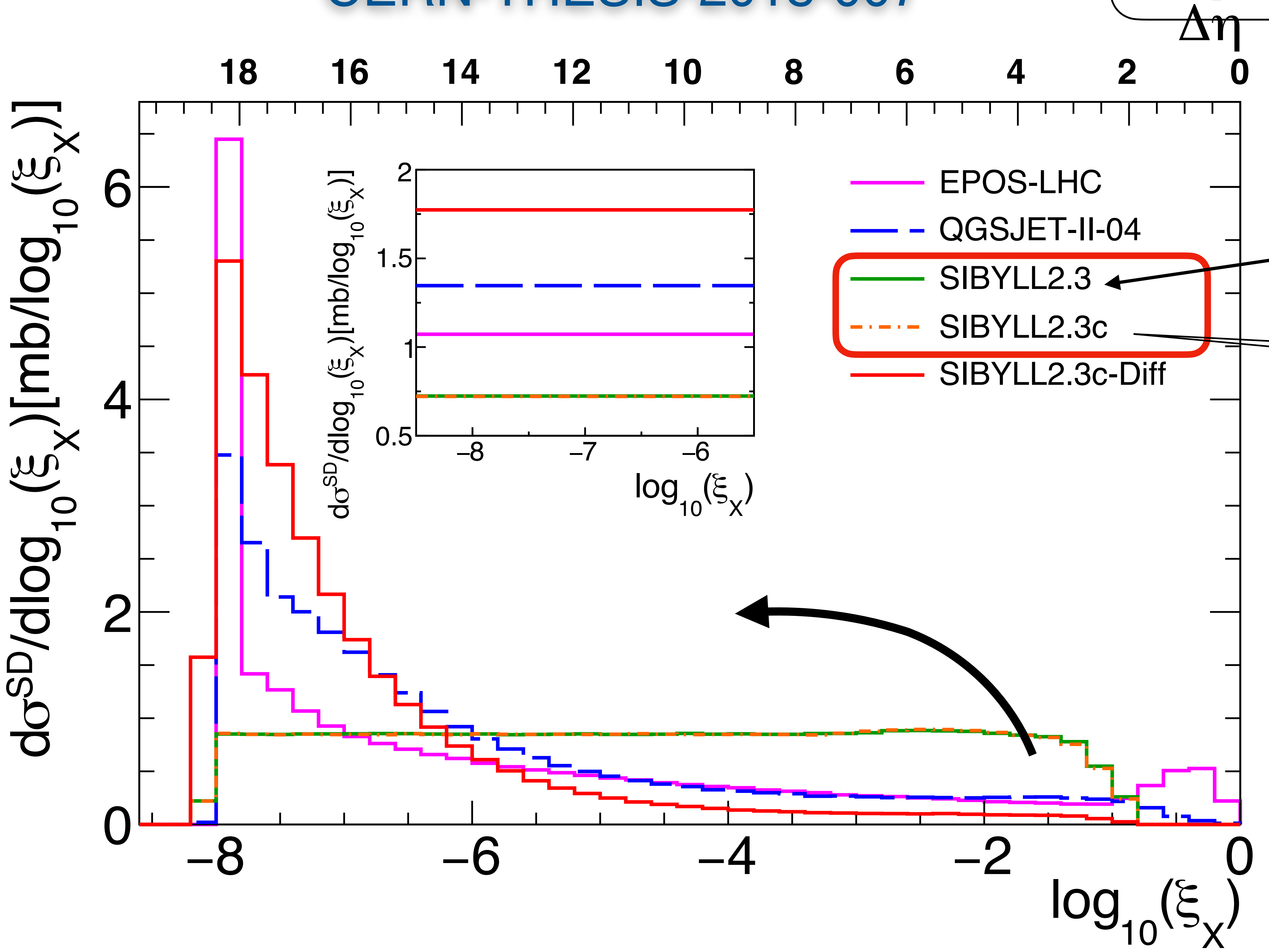
$$\xi_X = \left(\frac{M_X}{\sqrt{s}}\right)^2 \simeq e^{-\Delta\eta}$$: Momentum fraction lost by proton

$$\frac{d\sigma^{SD}}{d\xi_X dt} = f_P(\xi_X, t)\sigma(M_X^2) \propto \xi_X^{1-2\alpha_P(t)}((M_X^2)^{\alpha_P(0)-1})$$

pomeron flux — pomeron cross-section

$$\alpha_P(t) = \alpha_P(0) + \alpha'_P t = 1 + \Delta + \alpha' t$$: Pomeron trajectory

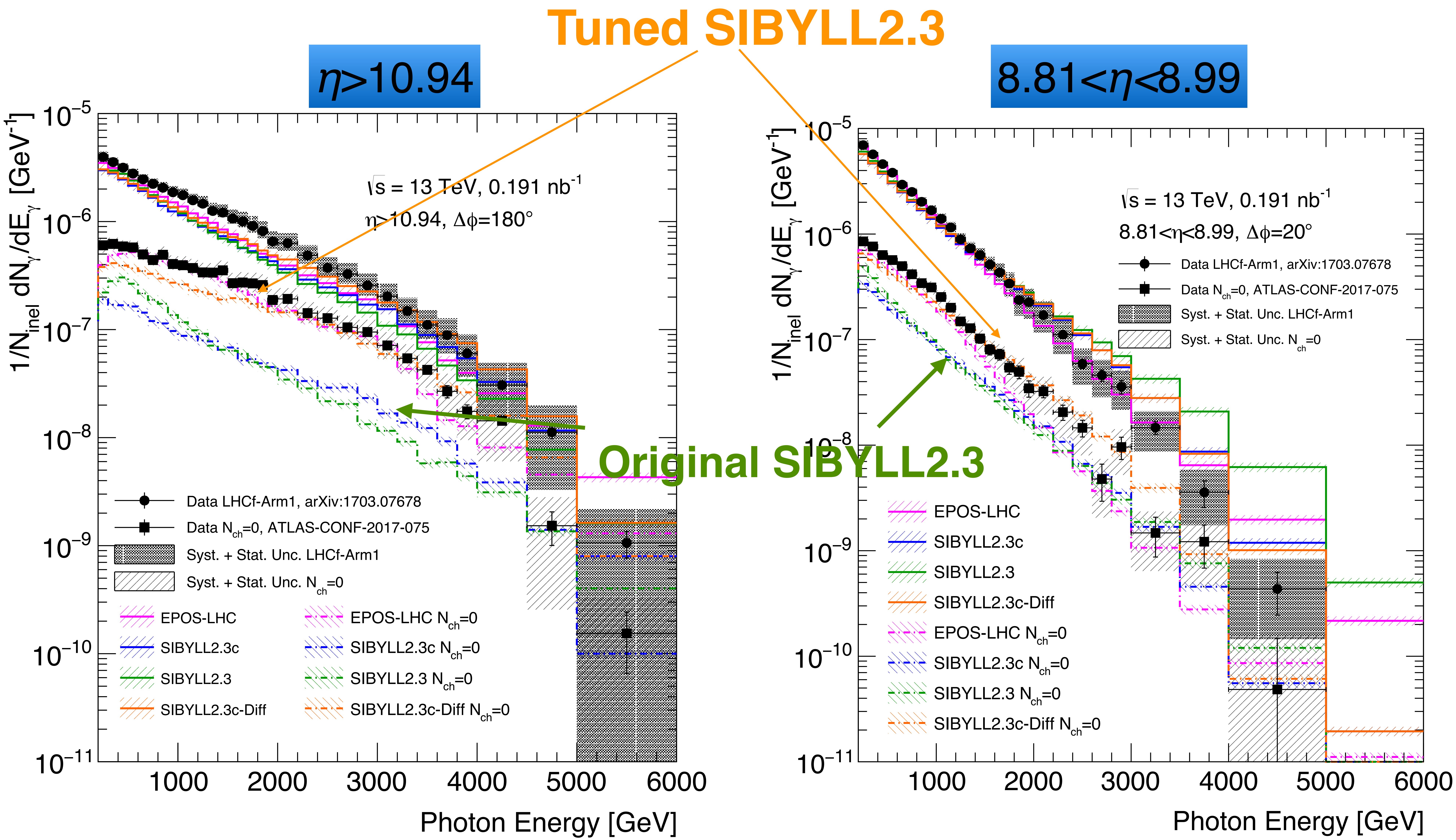
CERN-THESIS-2018-007



Original pomeron flux implemented in SIBYLL2.3

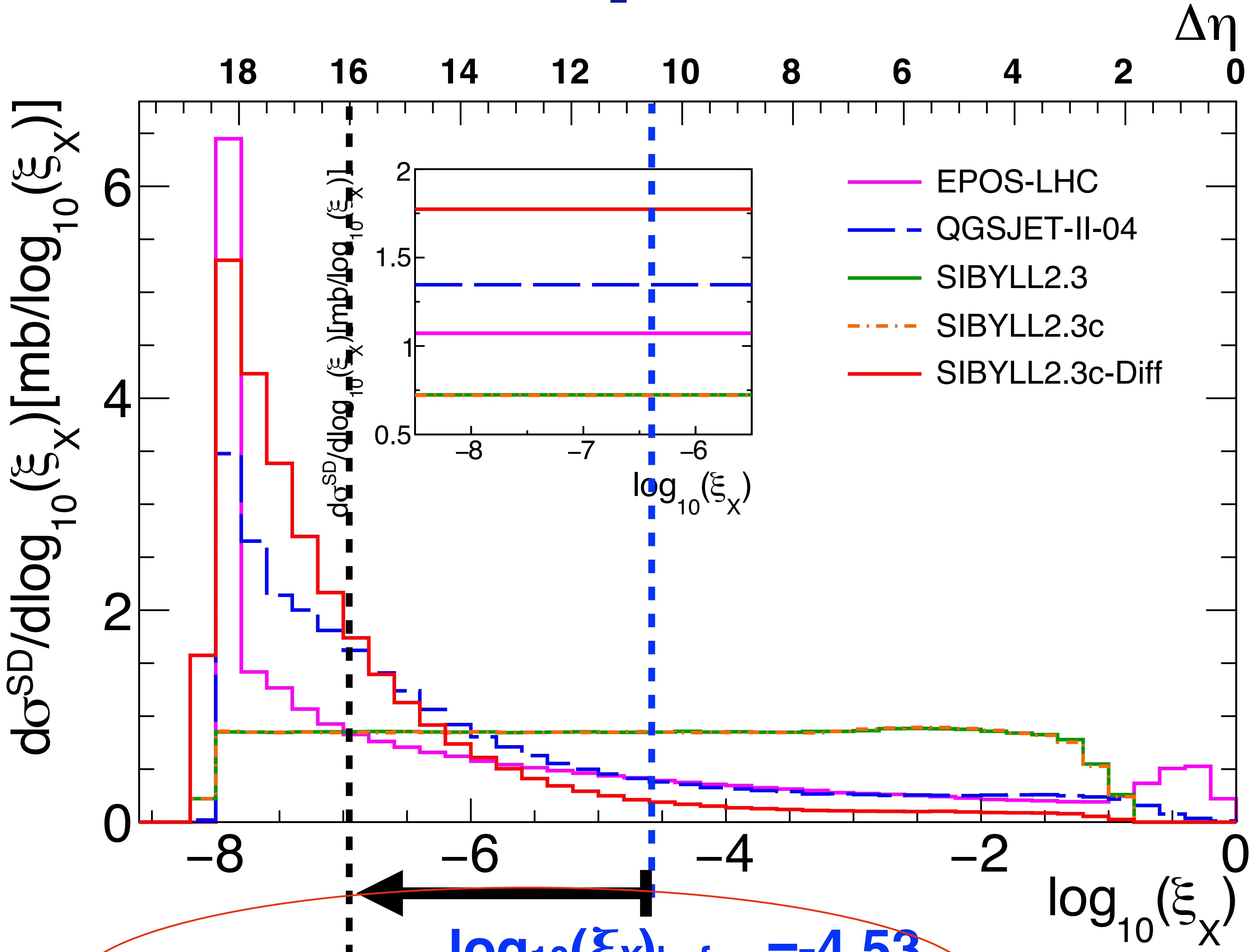
SIBYLL2.3c with the tuning of pomeron flux modified by **Felix Reihn** who is one of the editors of SIBYLL2.3

Spectra compare to SIBYLL2.3



SIBYLL2.3c-Diff improved a lot compare to joint analysis results

Impact to determination of X_{max}



$\log_{10}(\xi_X)_{before}$=-4.53

$\log_{10}(\xi_X)_{after}$=-6.92

average shift

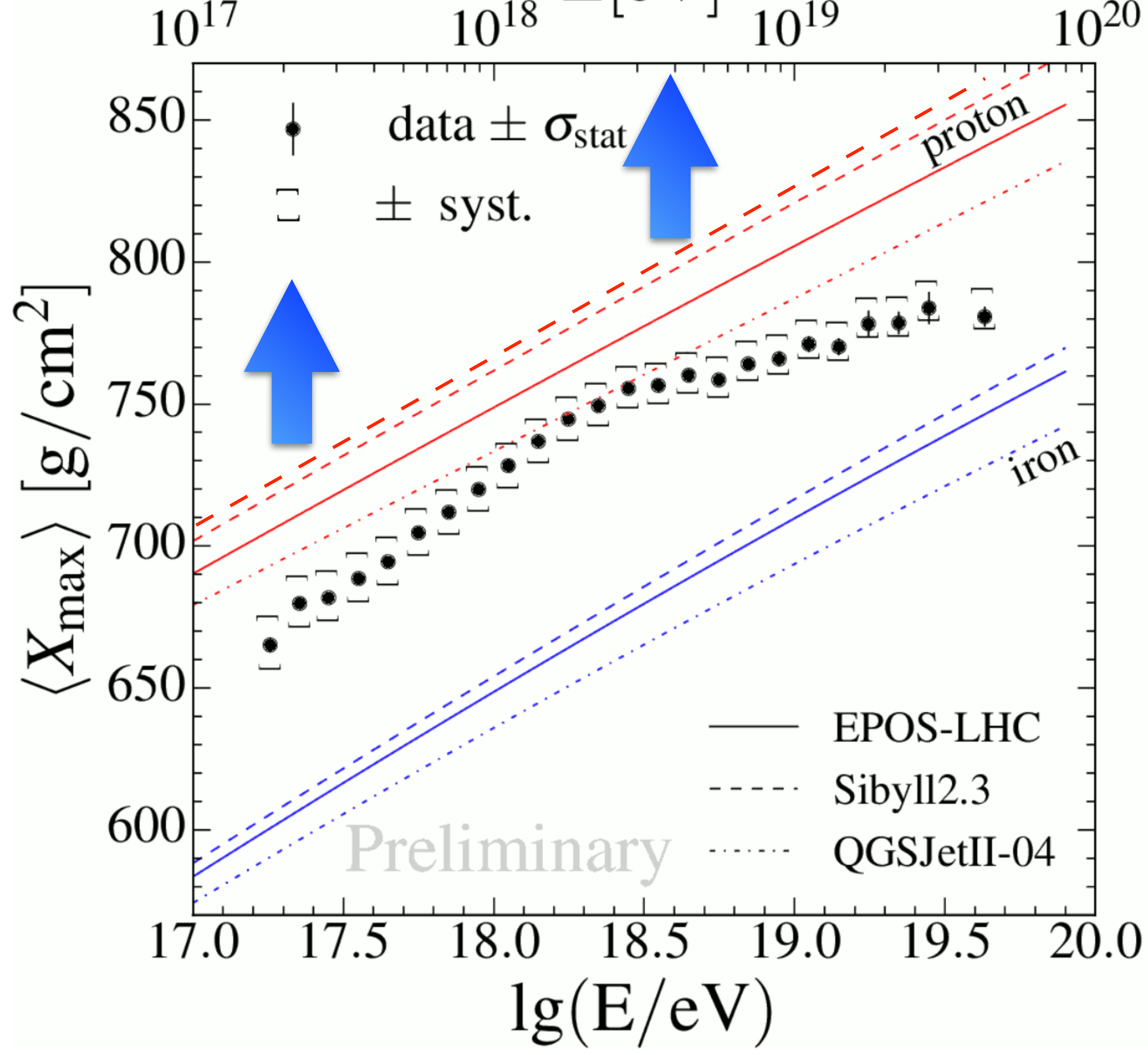
$$\kappa_{inela} \simeq \xi_X = (\frac{M_X}{\sqrt{s}})^2 \simeq e^{-\Delta\eta}$$

$$\Delta \log_{10}(\xi_X) = 2.39$$

$$\Delta X_{\max} \propto \frac{\lambda_e(\sigma_{SD}+\sigma_{DD})\Delta\log_{10}(\xi_X)}{\sigma_{inela}\ln 10} = 5.16 \text{ g/cm}^2$$

CERN-THESIS-2018-007

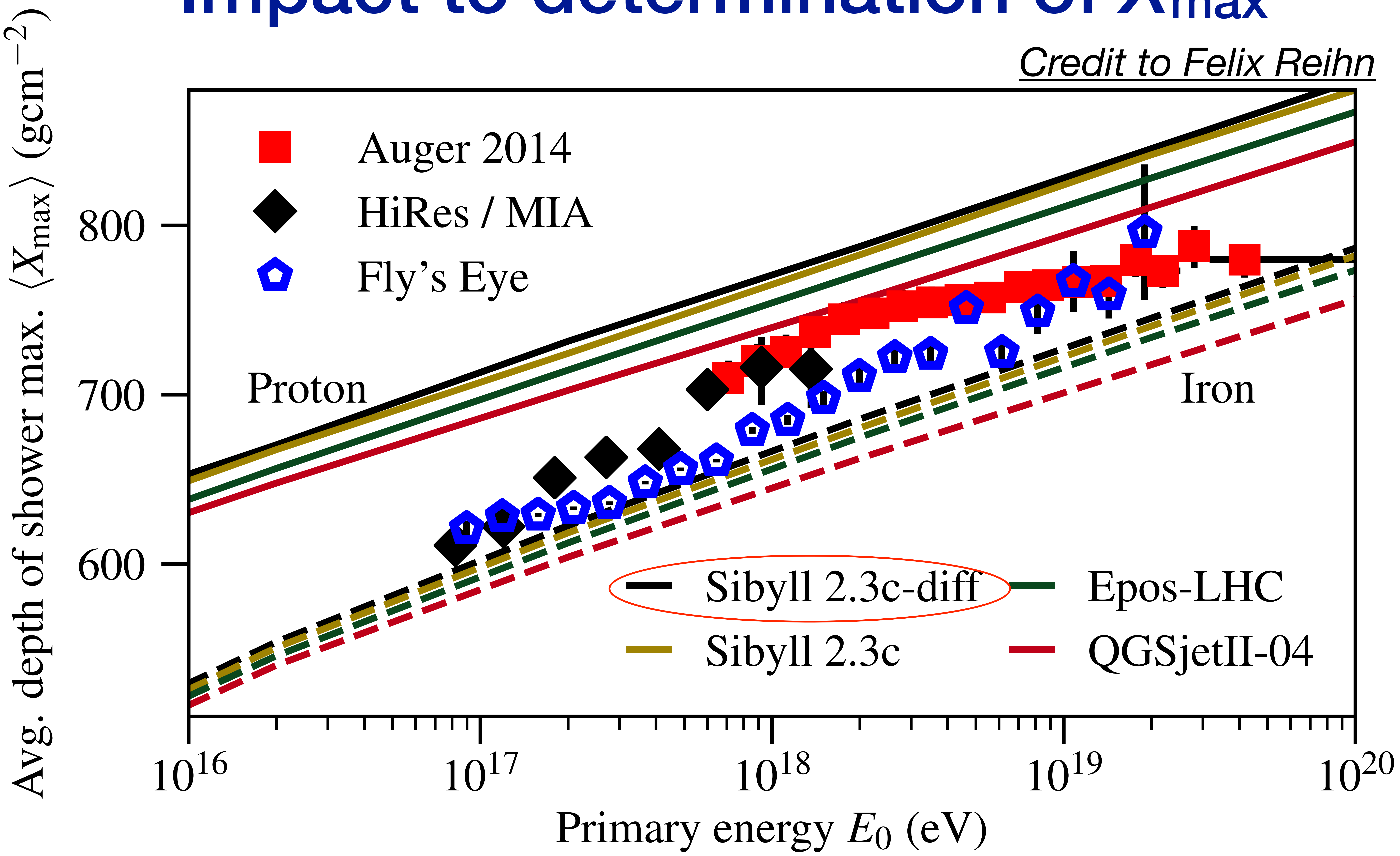
arXiv: 1708.06592



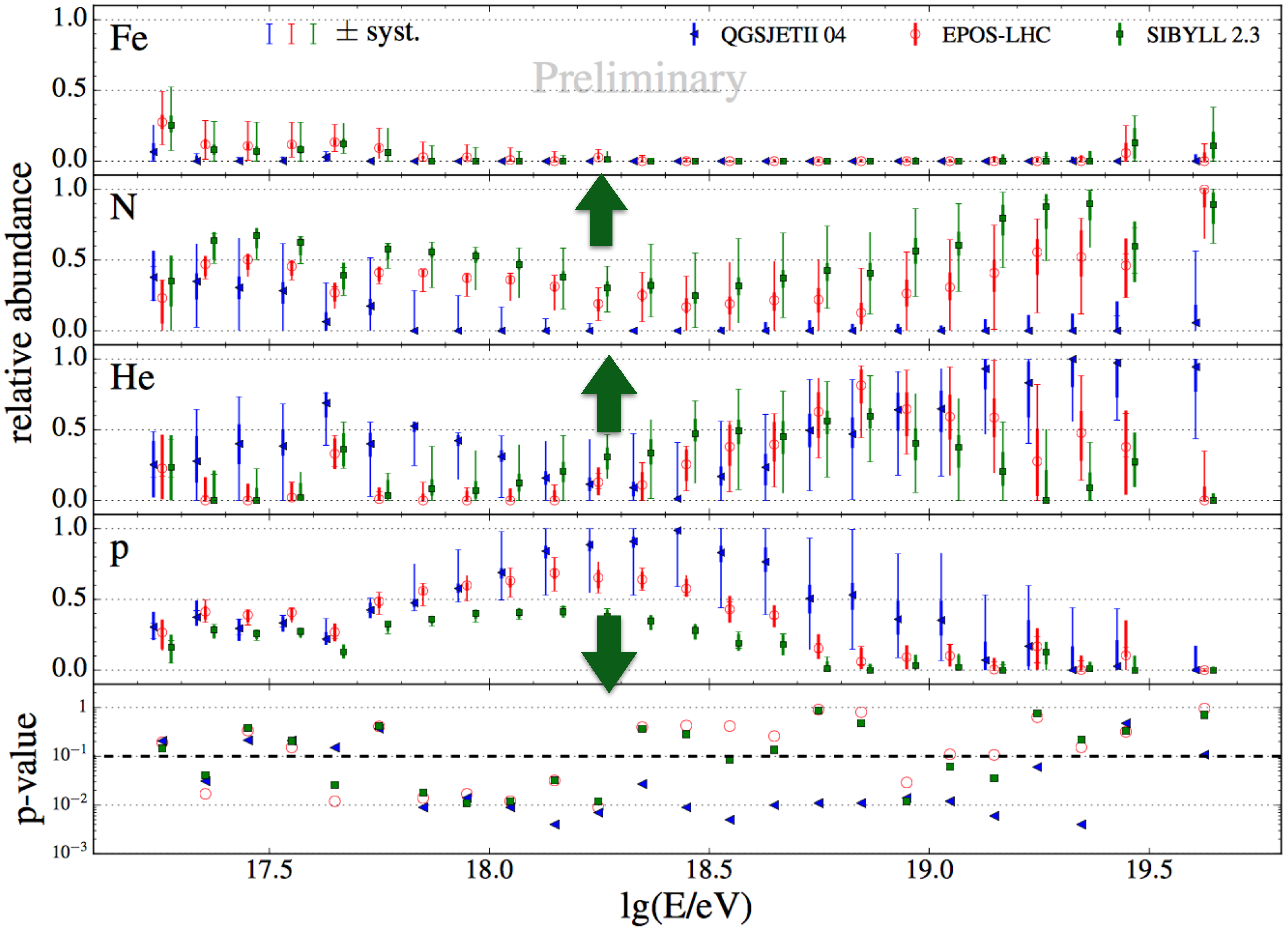
- Tuning of low-mass diffraction cross-section leads to the change of weighted average of $\log_{10}(\xi_X)$ from -4.53 to -6.92.
- X_{max} shifted up 5.16 g/cm² according to a rough calculation.

Impact to determination of X_{max}

Credit to Felix Reihn



Interpretation of nuclear composition



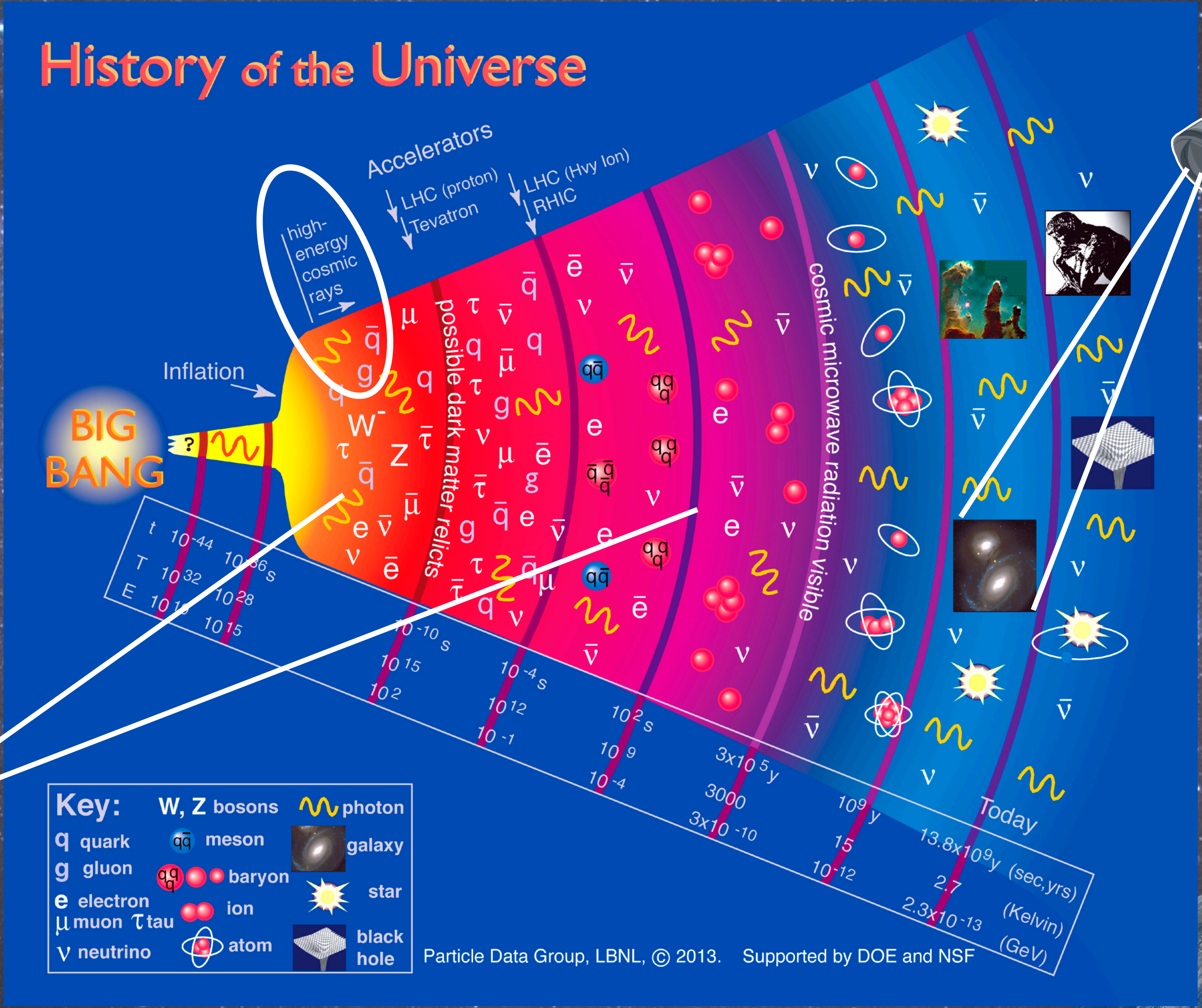
PAO, arXiv: 1708.06592

- Auger reproduced the observed X_{max} with the fractions fit of MC predictions.
- Considering X_{max} will shift to heavier direction with prediction of tuned SIBYLL2.3, it would prefer Helium and Nitrogen sources.

Short summary

- An adequate understanding of hadronic interactions is the key to solving the puzzling origin of UHECRs.
- LHCf is an experiment dedicated to measuring the neutral particle production at the very forward region, especially, the ATLAS-LHCf common experiment can explore the potential of both experiments for directly measuring the low-mass diffraction for the first time.
- It was confirmed that the low-mass diffraction measurement are very useful for constraining the implementation of diffractive dissociation, according to the tuning of SIBYLL2.3 model.
- Tuning of diffractive mass distribution has a strong correction with inelasticity, and shifted up X_{max} by 5.16 g/cm^2.
  - Interpretation of Auger X_{max} data based on tuned SIBYLL2.3 model shifted to heavier nuclear.

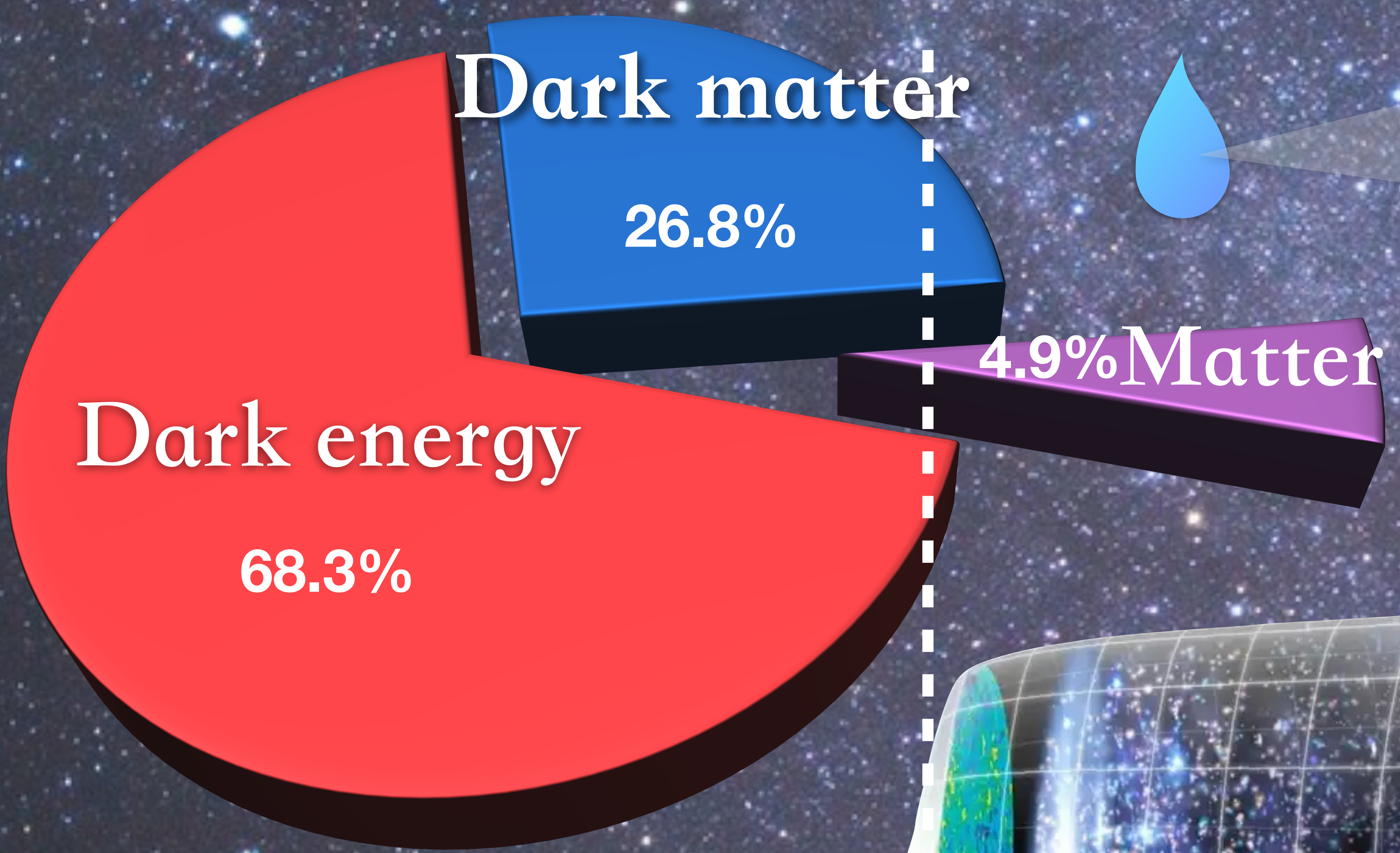
Back to the beginning of the universe



What is the origin of matter and the universe

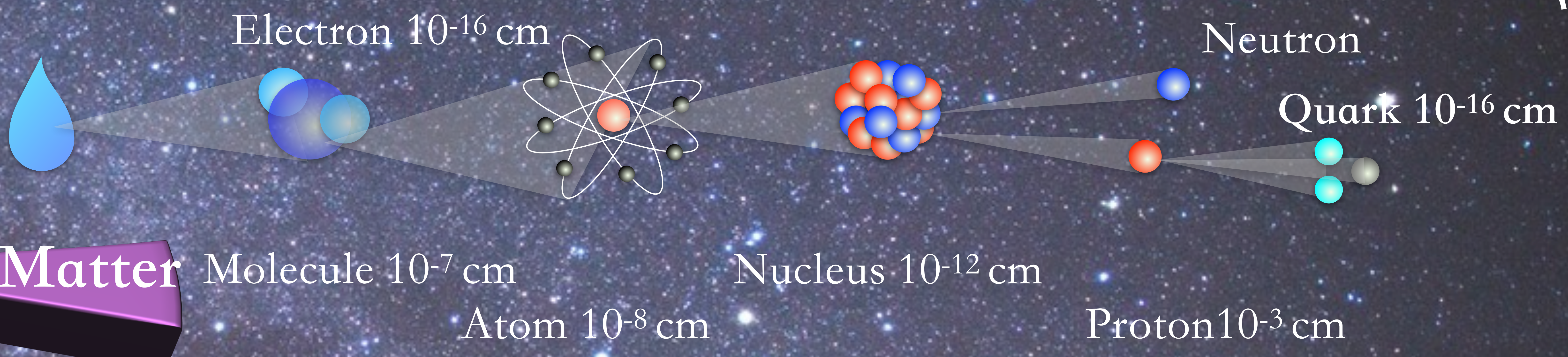
New physics

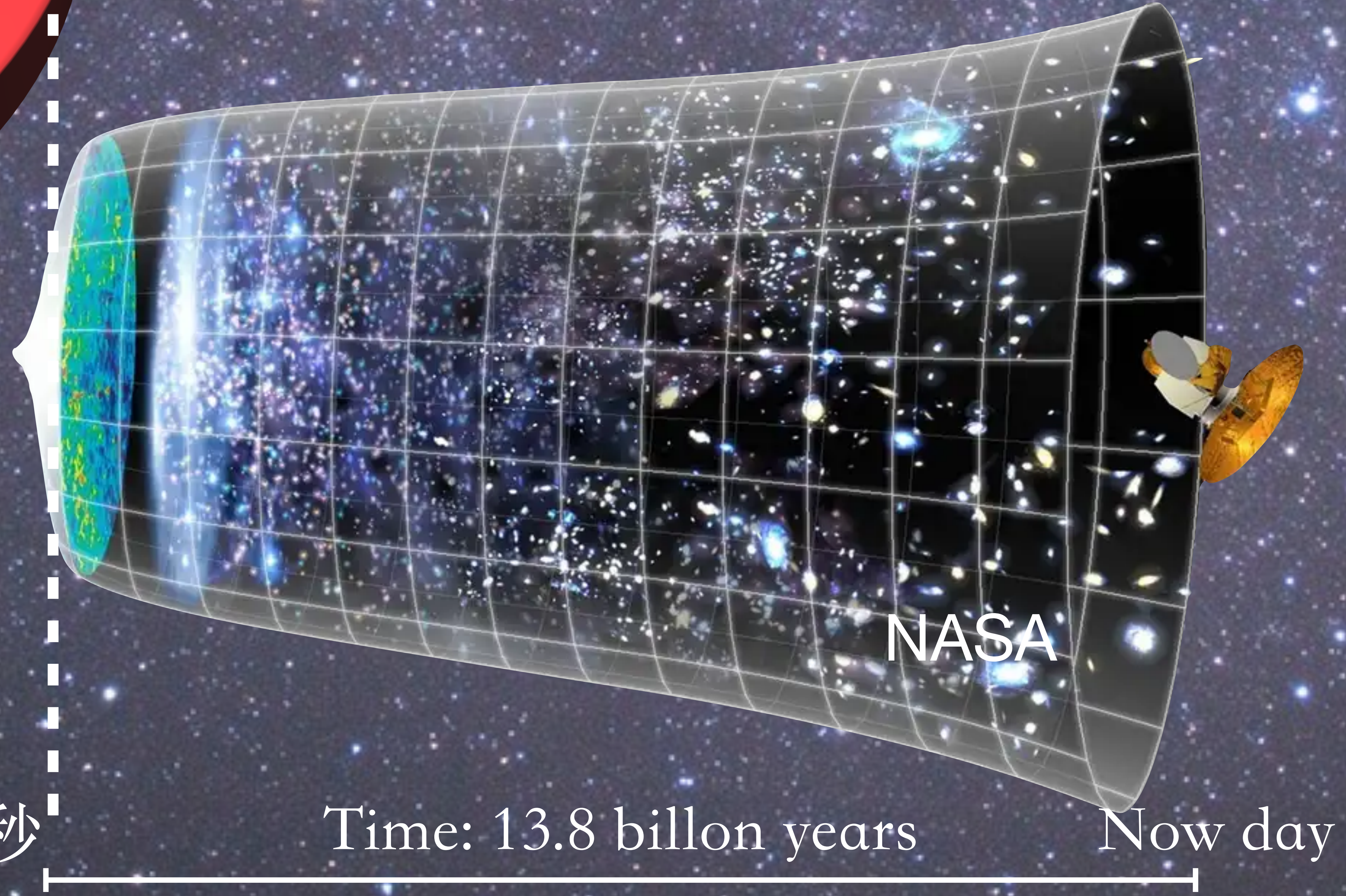
Standard model of particle physics

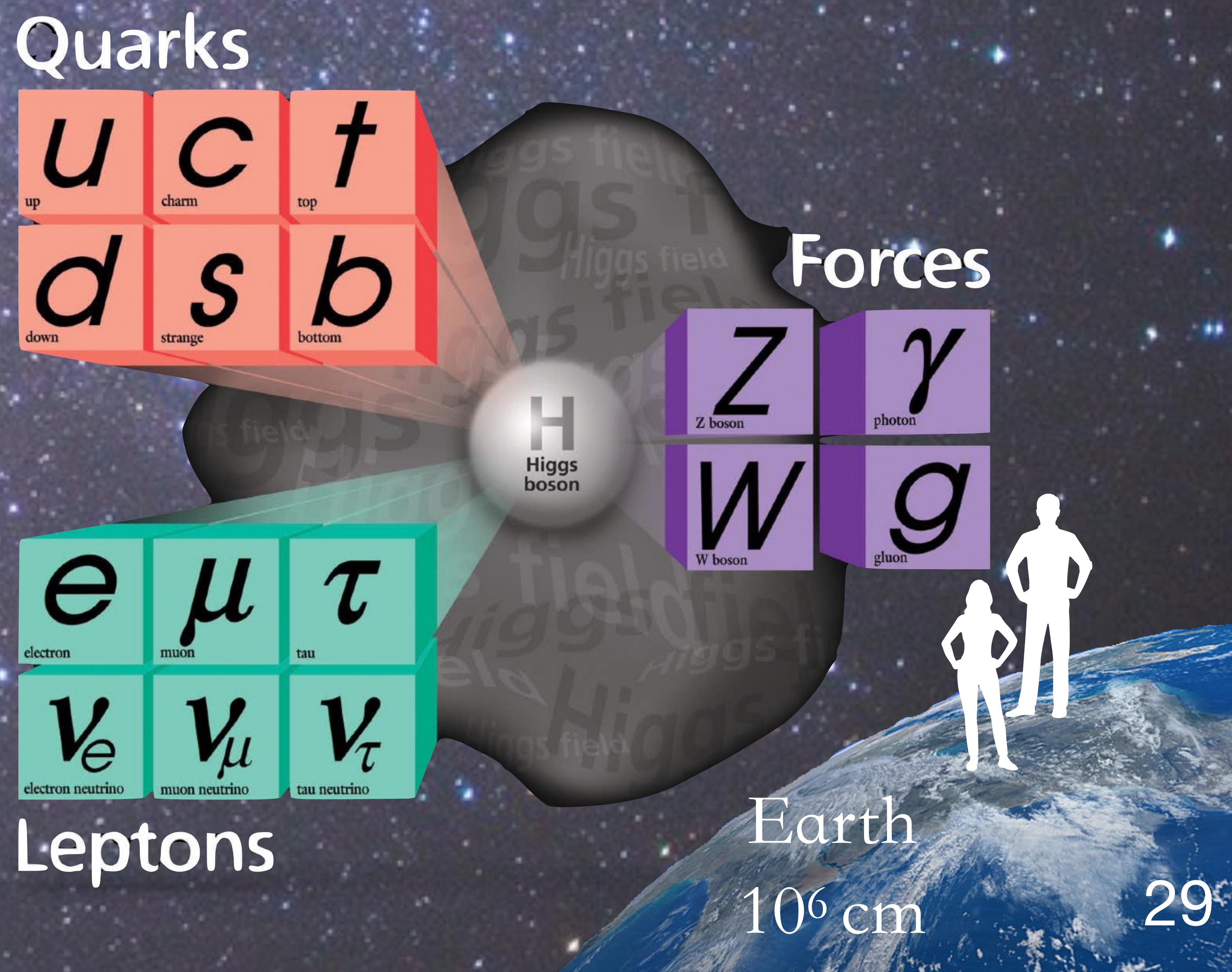


Matter-antimatter asymmetry ?

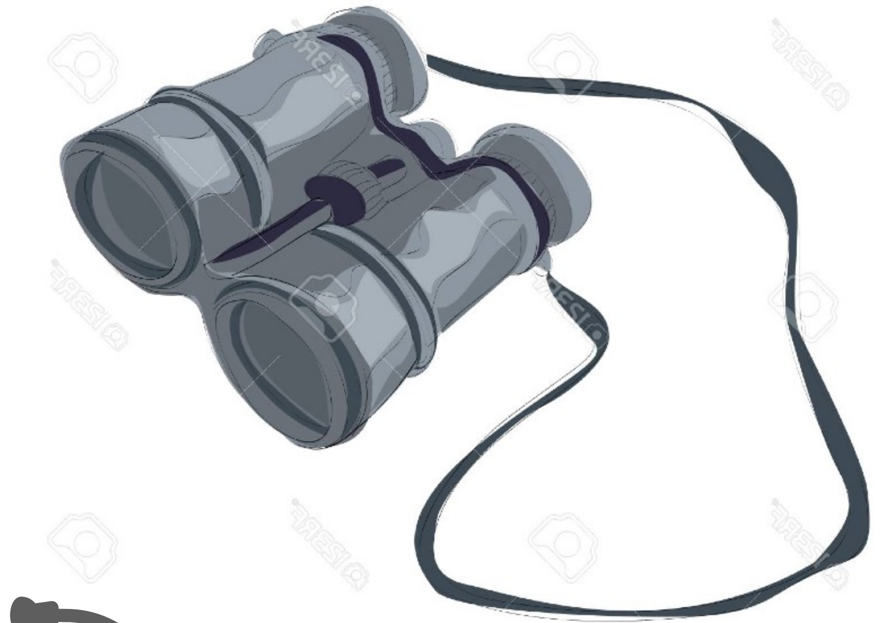
…





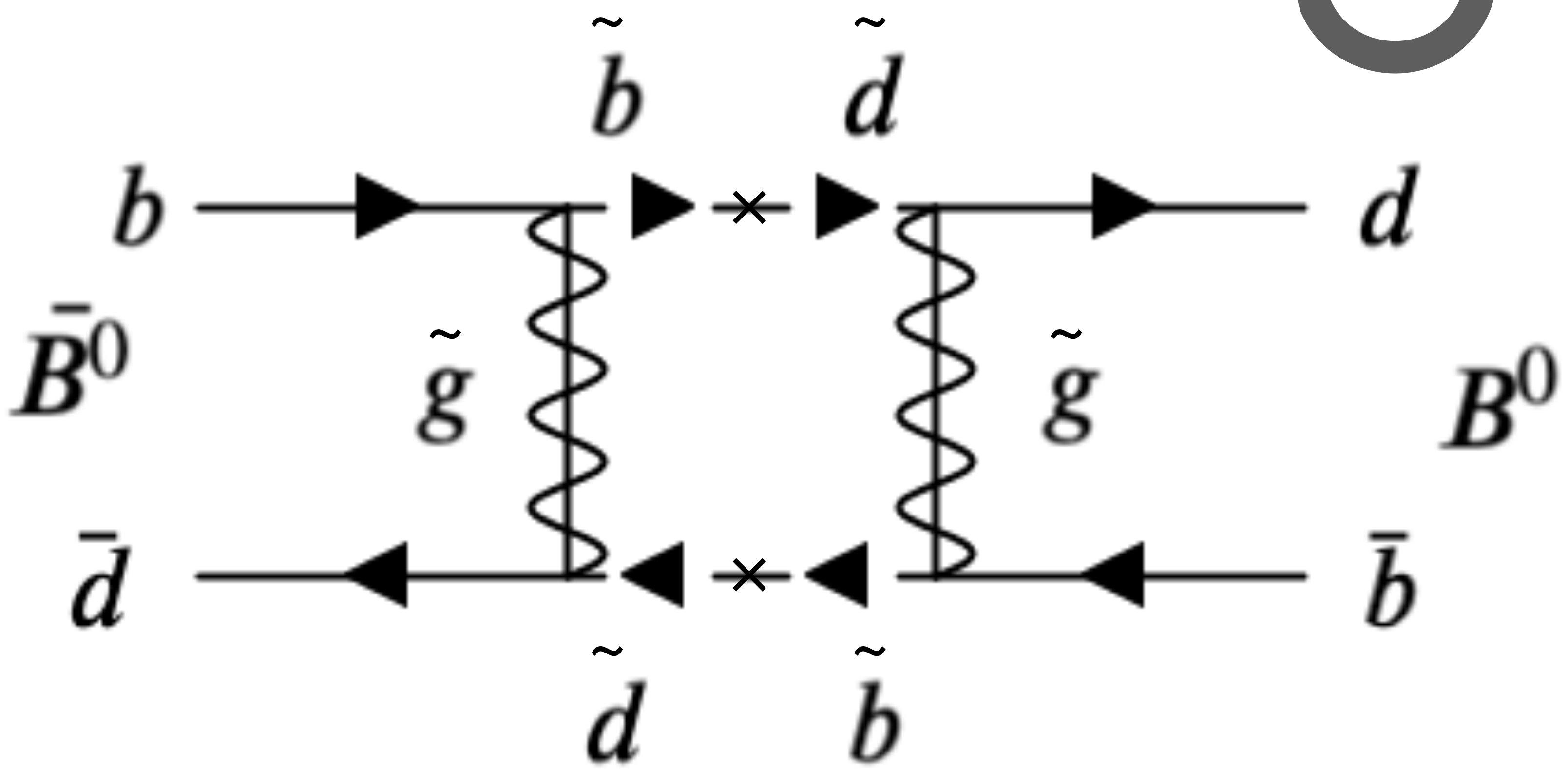


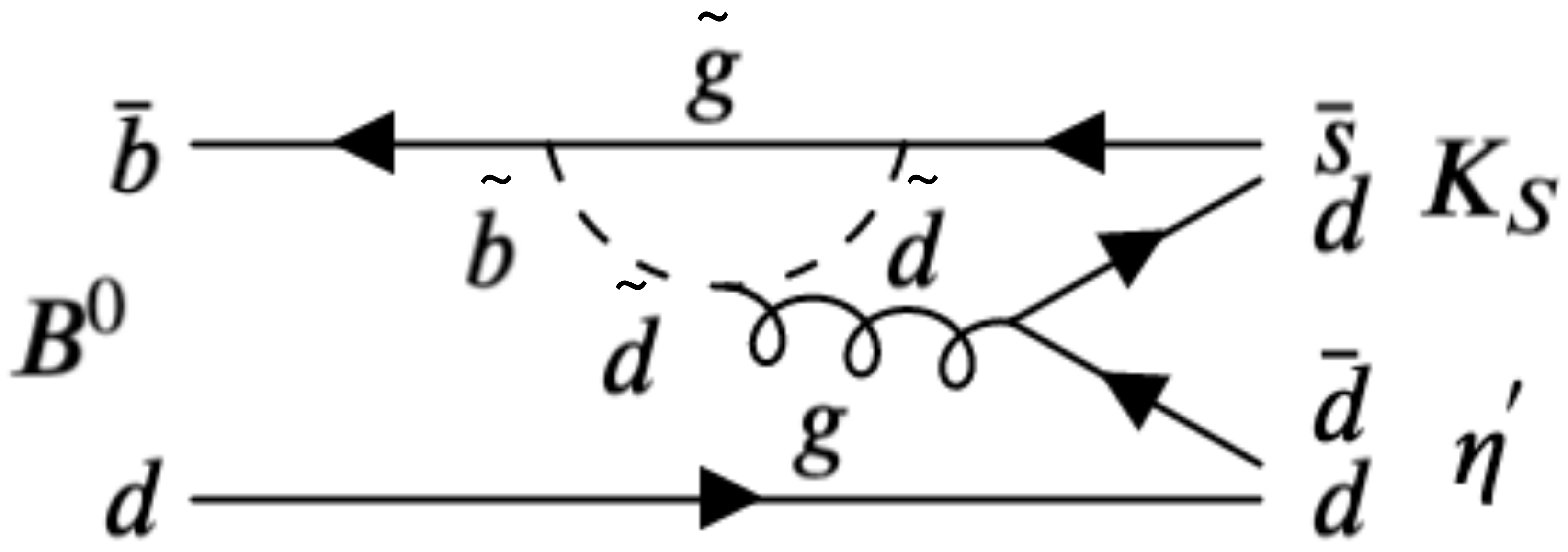
New physics search based on collider



Direct search at energy frontier

Indirect search at luminosity frontier : (Reactions produced pre second)

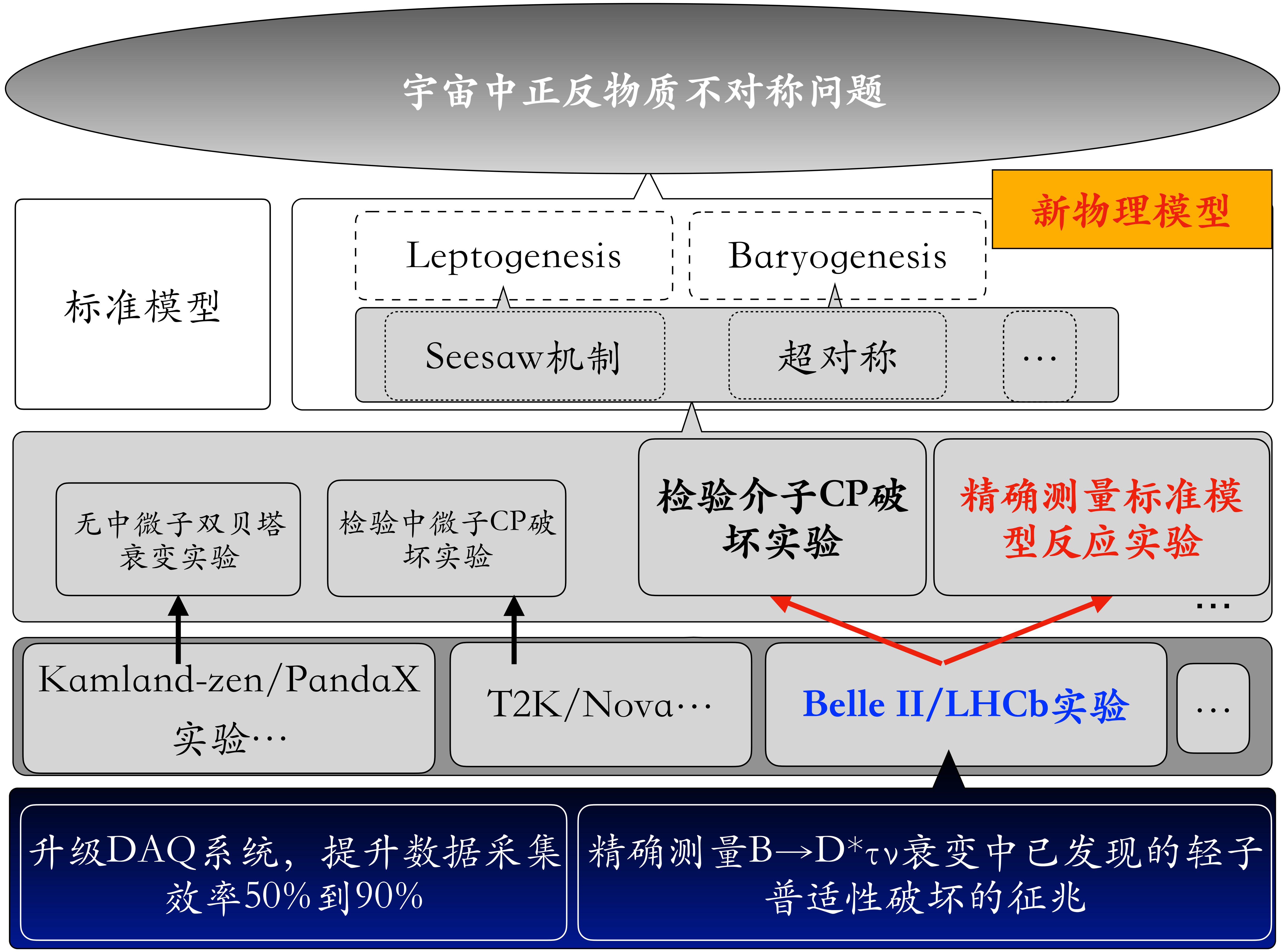




- Indirect search for New Physics (NP) in quantum effect
  - Sensitivity of NP detection up to **200 TeV** for loop diagram (depending on the NP coupling constant)

arXiv:1309.2293

Lepton Flavor Universality



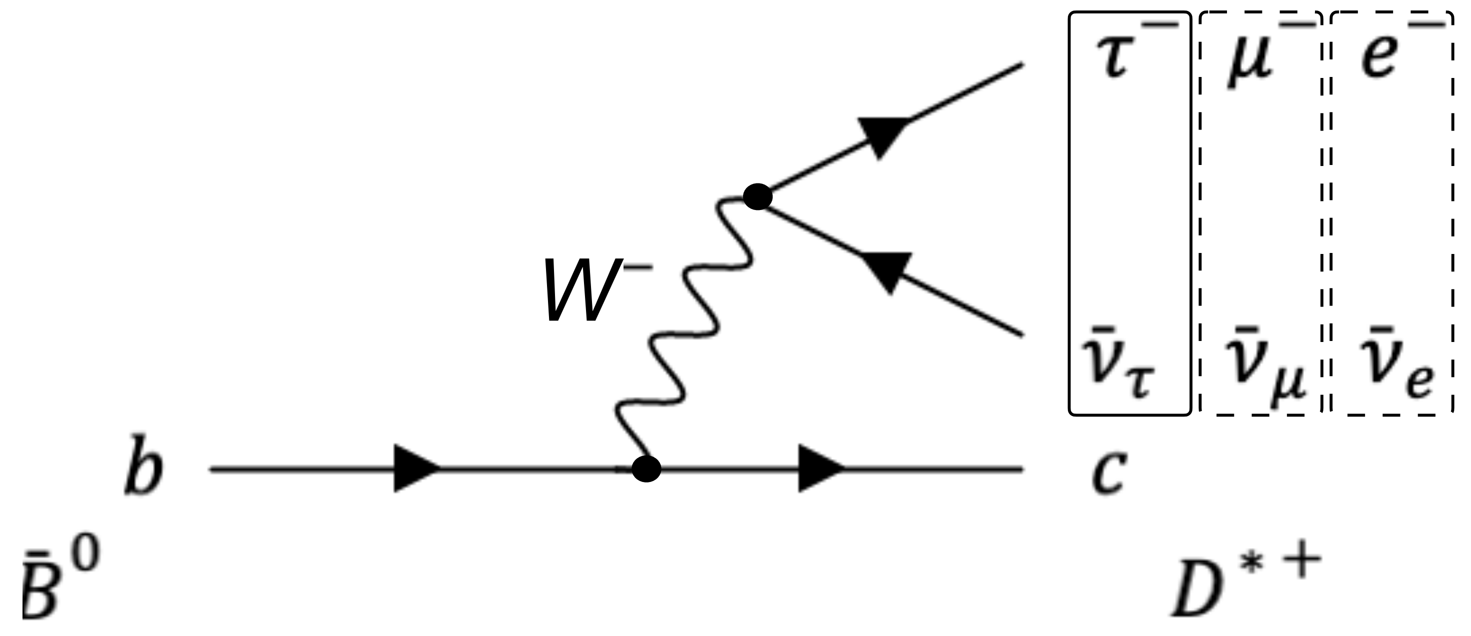
Lepton Flavor Universality

- Lepton Flavor Universality (LFU): A fundamental axiom of standard model is *W* boson couples, g_W, to **three generations** of leptons with **equal strength**
  - Description by matrix elements for leptonic and hadronic currents as a four Fermi interaction
  - Experiments confirmed LFU using W/Z boson decays, light meson decays, or lepton decays
- Difference in kinematics and Higgs coupling due to different lepton masses
  - Charged lepton mass changes kinematics and modifies form factors in the hadronization
  - QED corrections depend on lepton velocity (τ vs. ℓ (*e*, *μ*))

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{l}\gamma_\mu P_L \nu_l\right) + \text{h.c.}, \left(l = e, \mu, \tau\right)$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_W}{8M_W^2},$$

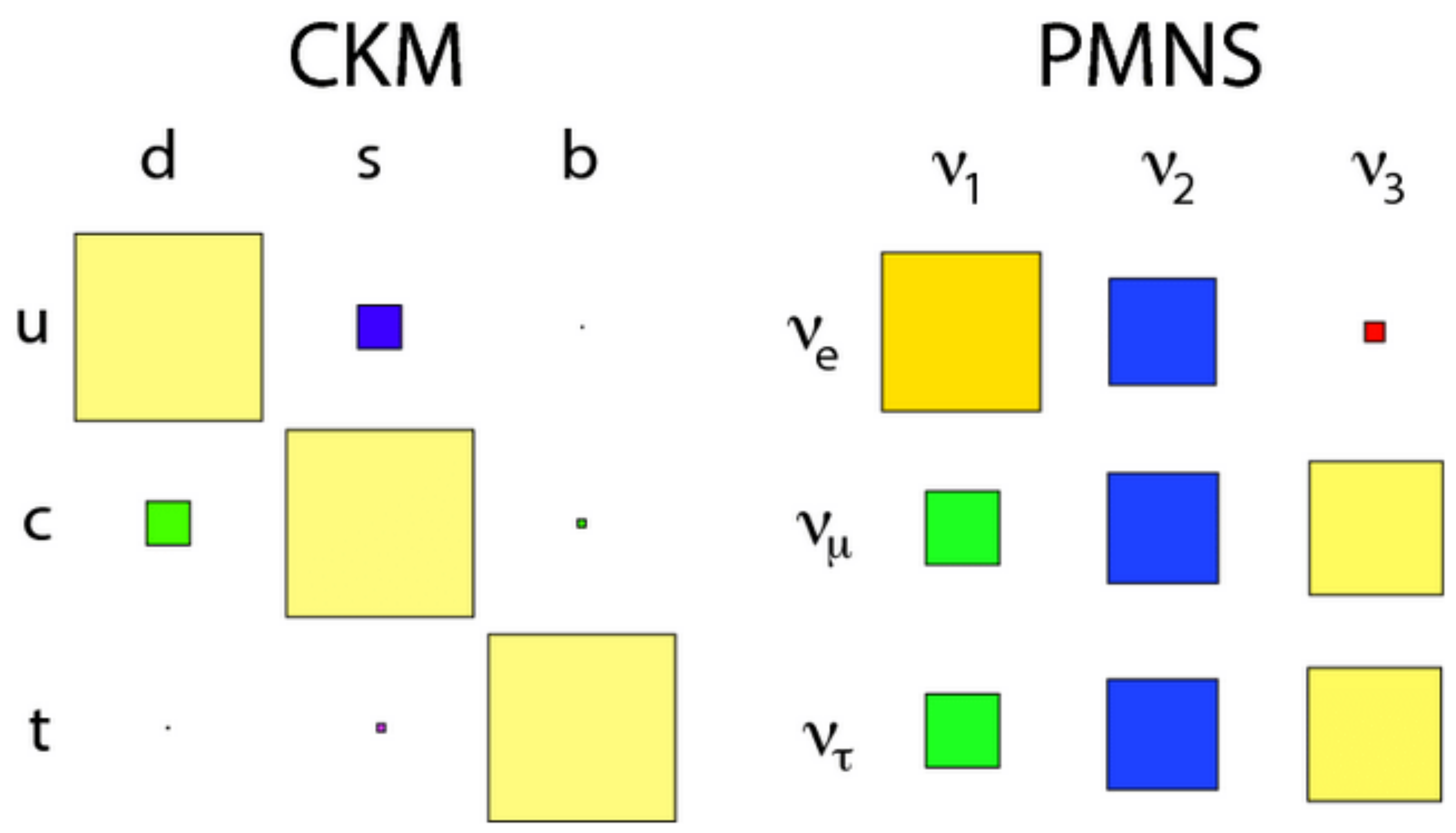
g_W: $SU(2)$ weak coupling constant



Motivation for studying LFUV

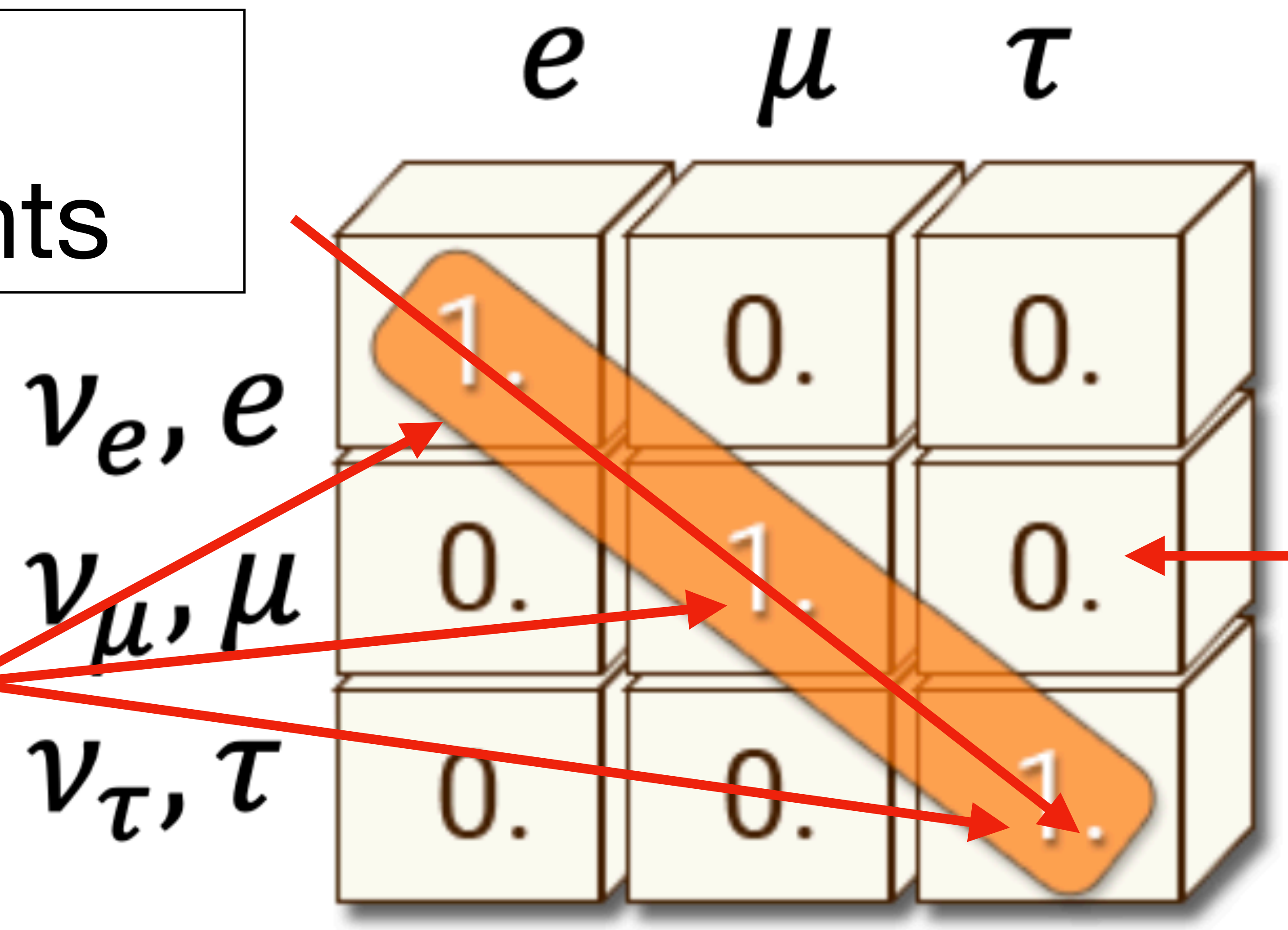
- SM fields do mix:
  - Quarks sector -> CKM matrix
  - Neutrinos sector -> PMNS matrix
- Charged leptons ->

  the matrix diagonal-like?(neutrino mass)
- LFUV: diagonal terms not all equal



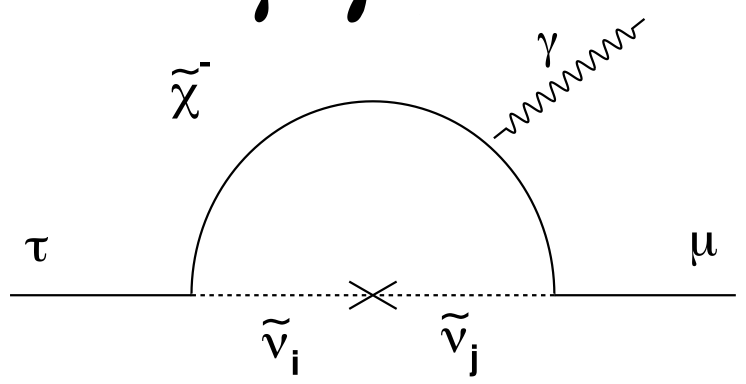
g-2, EDM:
diagonal elements

LFUV:
Relation among
diagonal elements



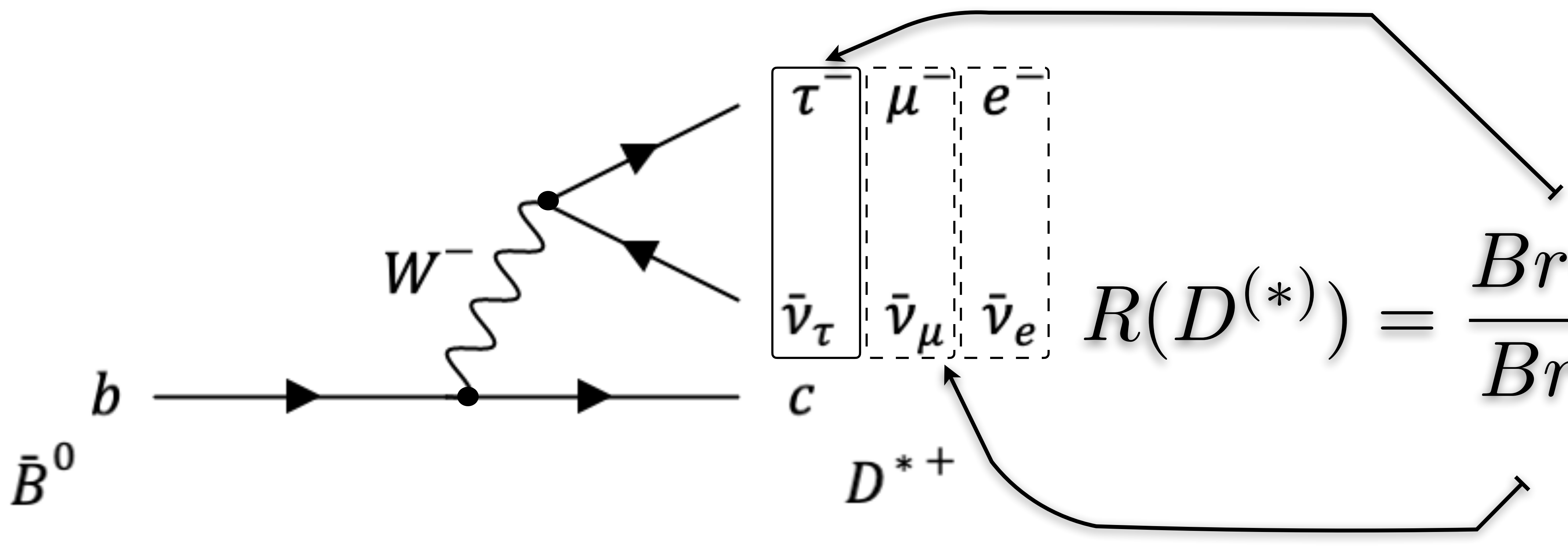
Lepton Flavor Violation (LFV):
off diagonal term

$\tau \to \mu\gamma$

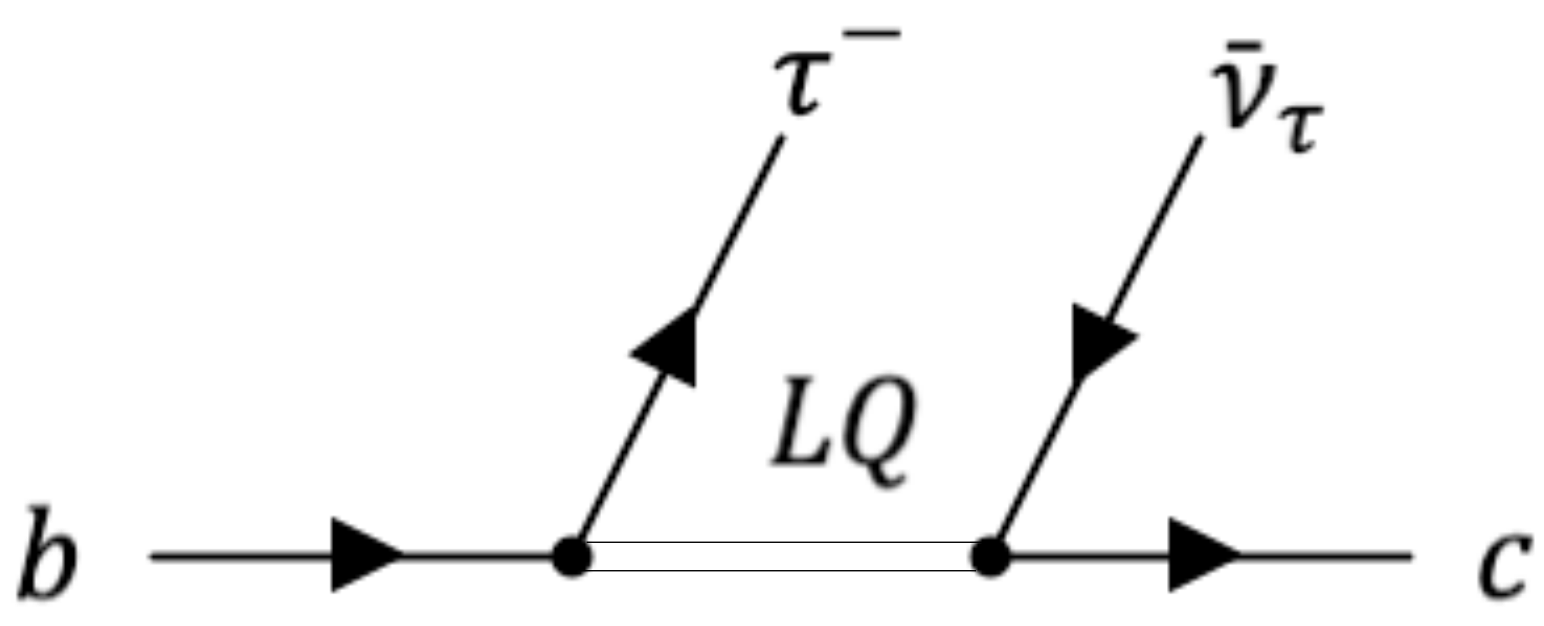


LFU test with semileptonic B decays

- Ratios of $b \to q\tau\nu / q\mu\nu / qe\nu$ branch fractions cancel out most of the uncertainties on $|V_{cb}|$, **form factors** and the **experimental systematics**
- $B \to D^{(*)}\tau\nu$ sensitive to New Physics (NP) because the massive 3rd generation b quark and τ lepton are involved
- Sensitivities to high energy scale; ~10 TeV [Belle II phys. book]

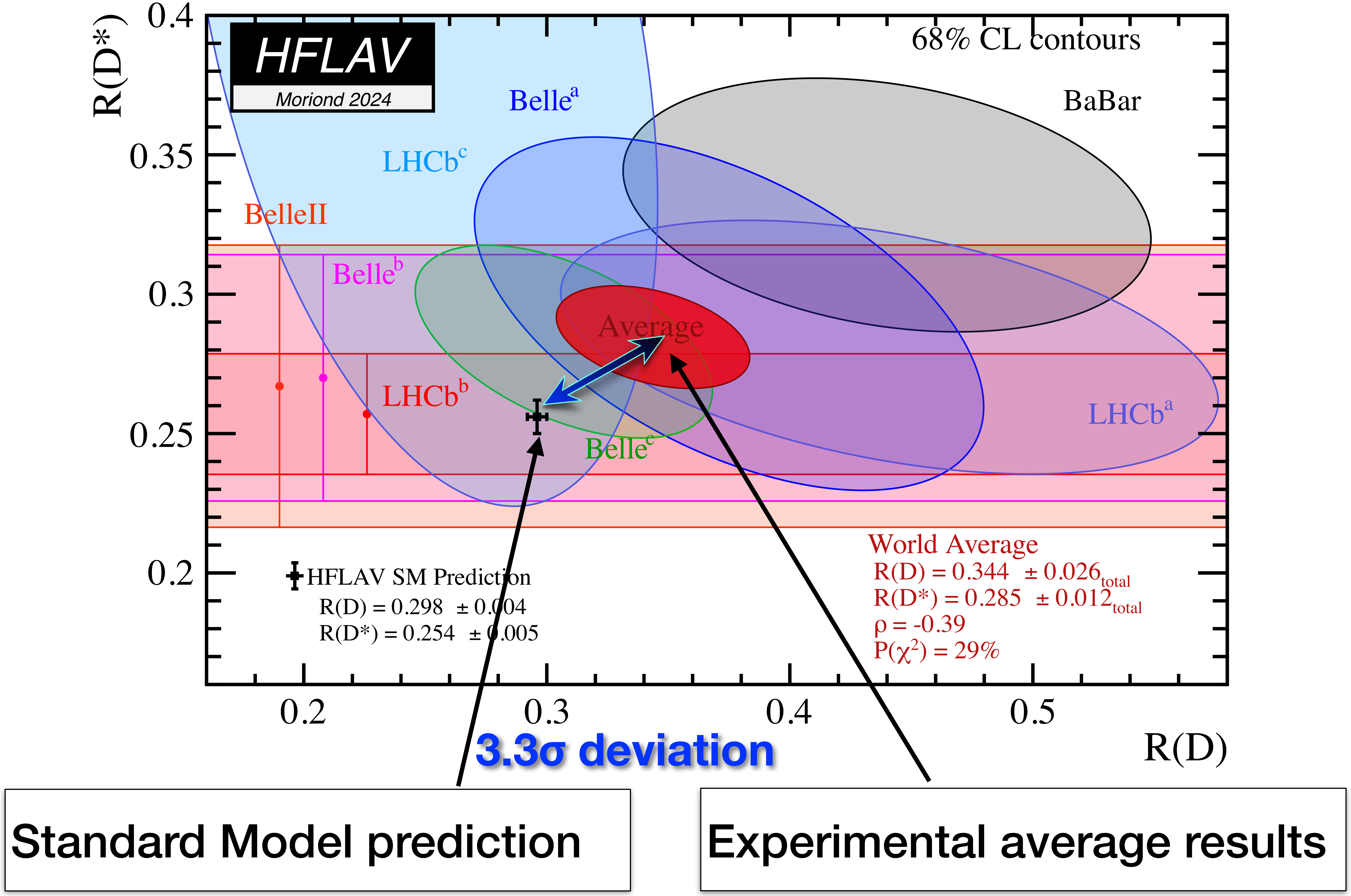


$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$



		Branching fraction [%]	
		$\mathcal{B}(B^0)$	$\mathcal{B}(B^+)$
World average ($\ell = e$ or μ)	$\overline{B} \to X_c \ell^- \overline{\nu}_\ell$	10.1 ± 0.4	10.8 ± 0.4
	$\overline{B} \to D^* \ell^- \overline{\nu}_\ell$	5.41 ± 0.11	5.03 ± 0.11
SM	$\overline{B} \to D^* \tau^- \overline{\nu}_\tau$	~ 1.37	~ 1.28

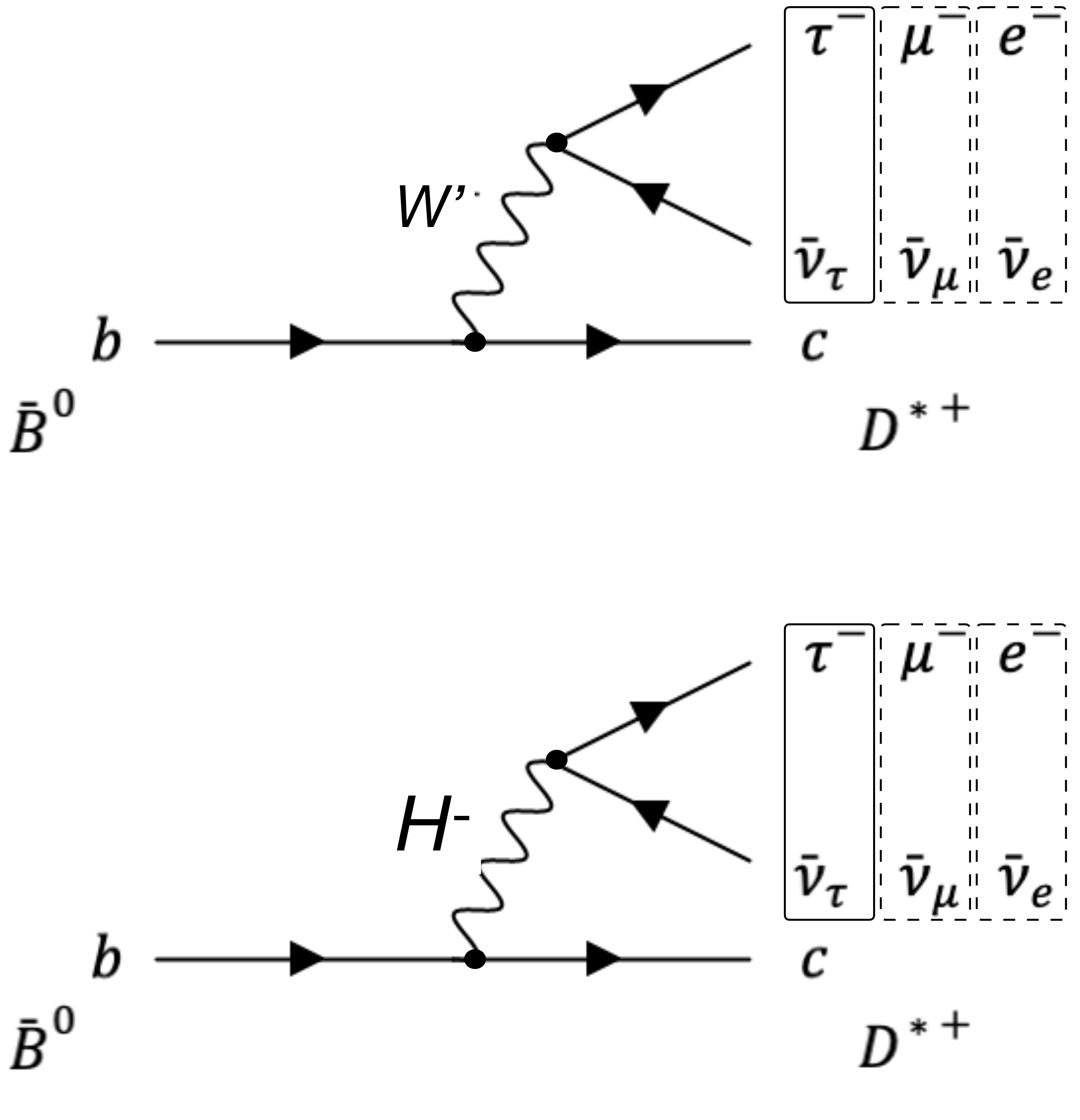
“*B* anomaly” in semileptonic decays

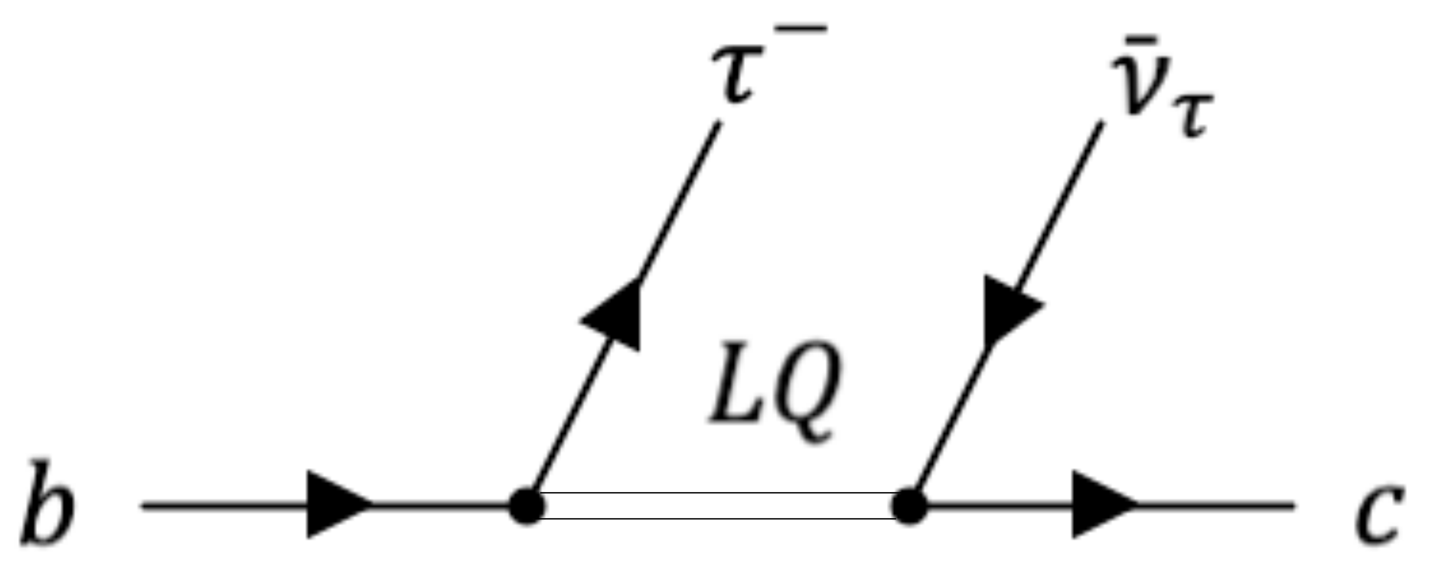


New physics scenarios for the $R(D^{(*)})$ anomaly

In general, there are three typical candidate scenarios to explain the anomaly observed in $R(D^{(*)})$

- Heavy vector bosons
  - Constrained from $W' \to \tau\nu$ and $Z' \to \tau\tau$ search
- Charged Higgs
  - Constrained from $B_c \to \tau\nu$ and $H^{\pm} \to \tau\nu$,still allowed
  - Previously, it was rejected by $B_c \to \tau\nu$ measurement, however, recovered by recalculating the B_c lifetime.
    PRD 105 095011(2022)
- Leptoquark
  - $gg \to LQ\ LQ^*$, still broad parameter regions are allowed





LFU test program at Belle and Belle II

- The analyses presented in this talk
  - **$R_{\tau/l}$ (D^*) at Belle II (189 fb^{-1}), PRD 110 072020 (2024)**
  - **$R_{\tau/l}$ (X) at Belle II (189 fb^{-1}), PRL132, 211804 (2024)**
  - ~~$R_{e/\mu}$(X) from Belle II (189 fb^{-1}), PRL 131, 051804 (2023)~~
  - ~~$R_{e/\mu}$(D^*) from Belle (711 fb^{-1}), PRD 108, 012002 (2023)~~
  - ~~Test of LFU in angular asymmetries of $B \to D^* l\nu$ at Belle II (189 fb^{-1}), PRL 131, 181801 (2023)~~

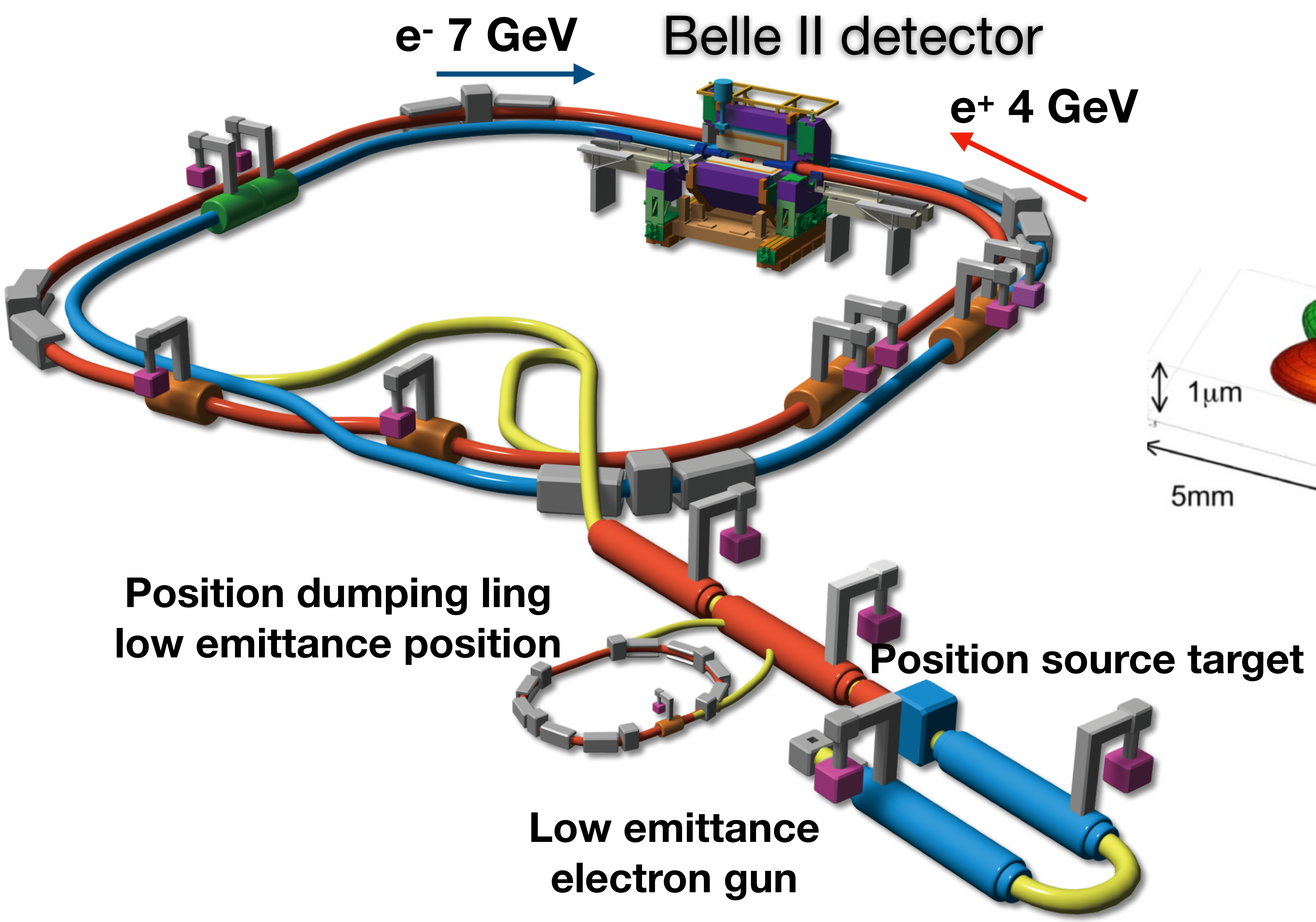
Luminosity frontier: SuperKEKB

- Asymmetric e^+e^- collider
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - very clean and well-known initial state

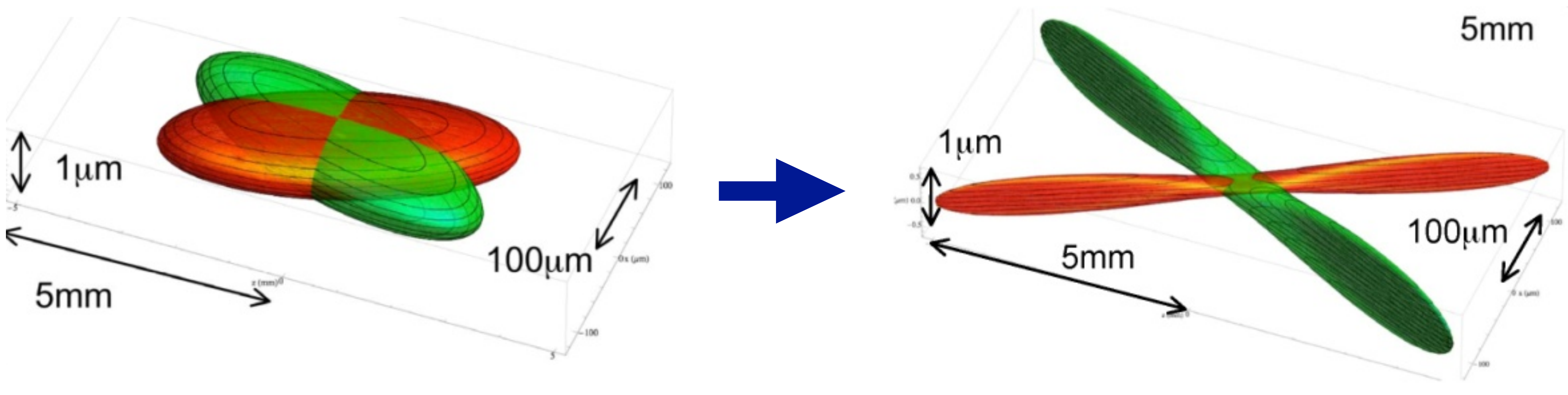
Beam current: KEKB x ~1.5

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Beam squeeze: KEKB / ~20



Nano beam scheme



Target: L = 60 x 10^{34} cm^{-2} s^{-1}
Achieved : 4.7 x 10^{34} cm^{-2} s^{-1} (Record)

- Data:
  - **571** fb^{-1} (Belle II) <-> 980 fb^{-1} (Belle)

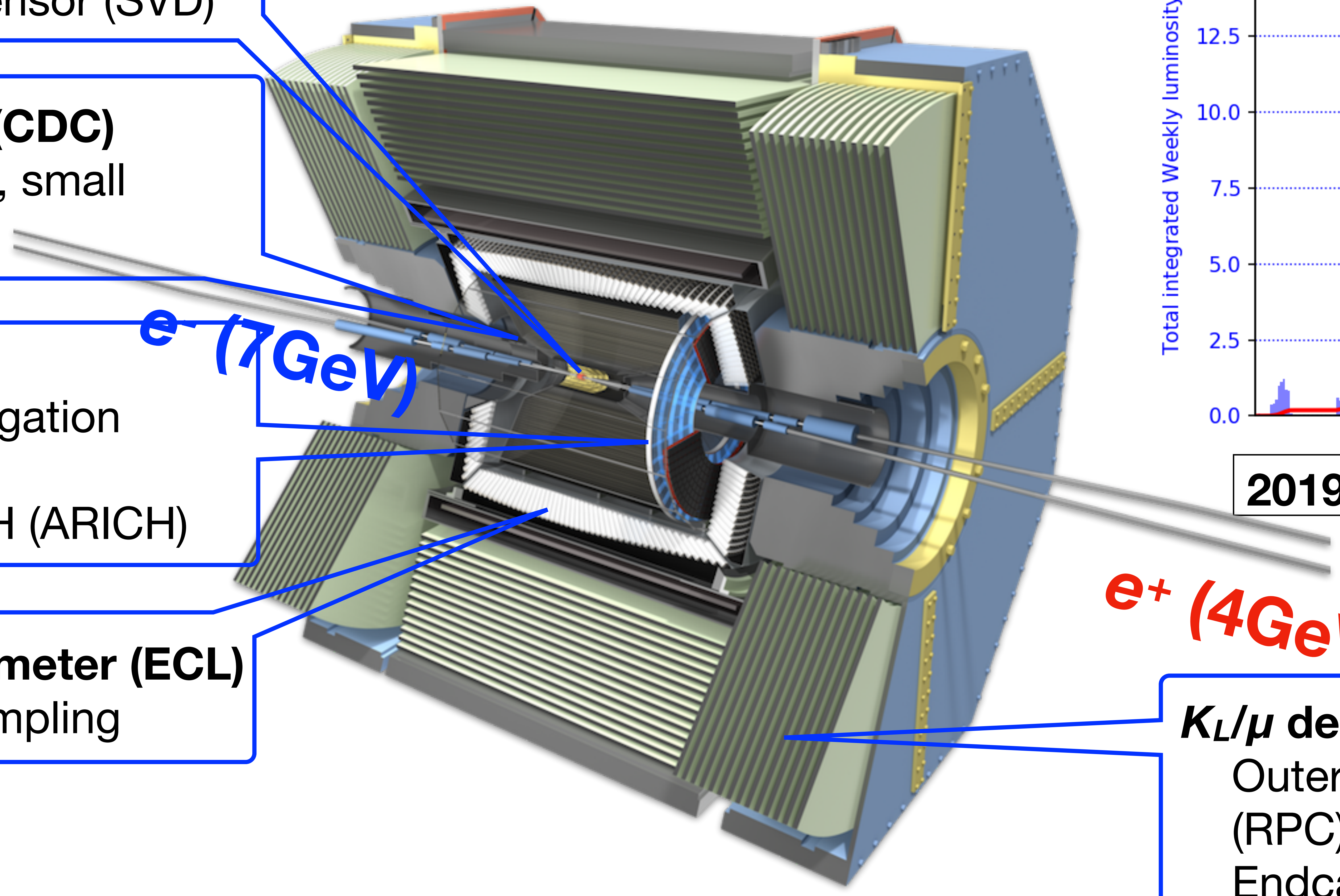
Belle II detector and dataset

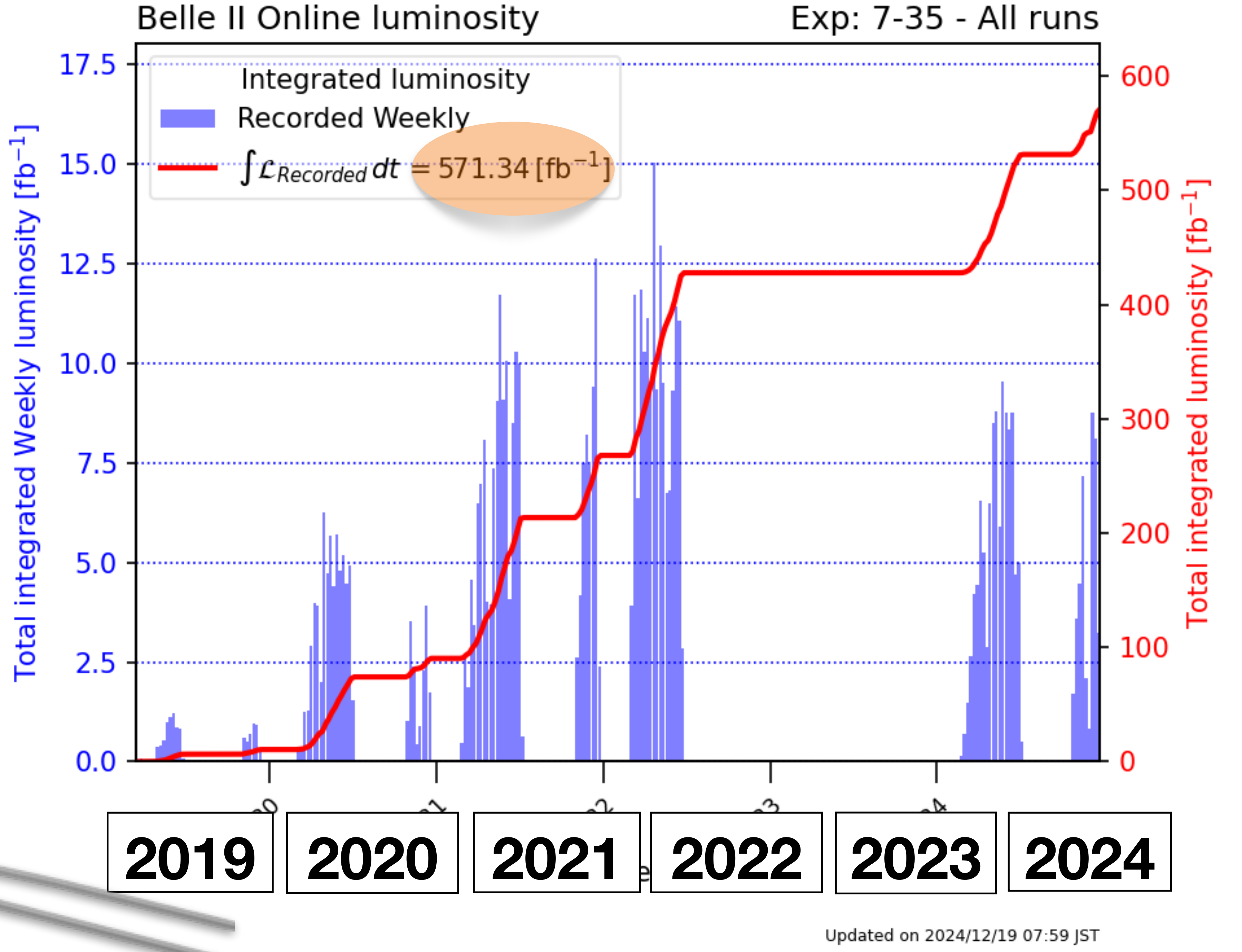
Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

Central Drift Chamber (CDC)
He (50%), C_2H_6 (50%), small cells, long lever arm

Particle Identification
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)

ElectroMagnetic Calorimeter (ECL)
CsI(Tl) + waveform sampling



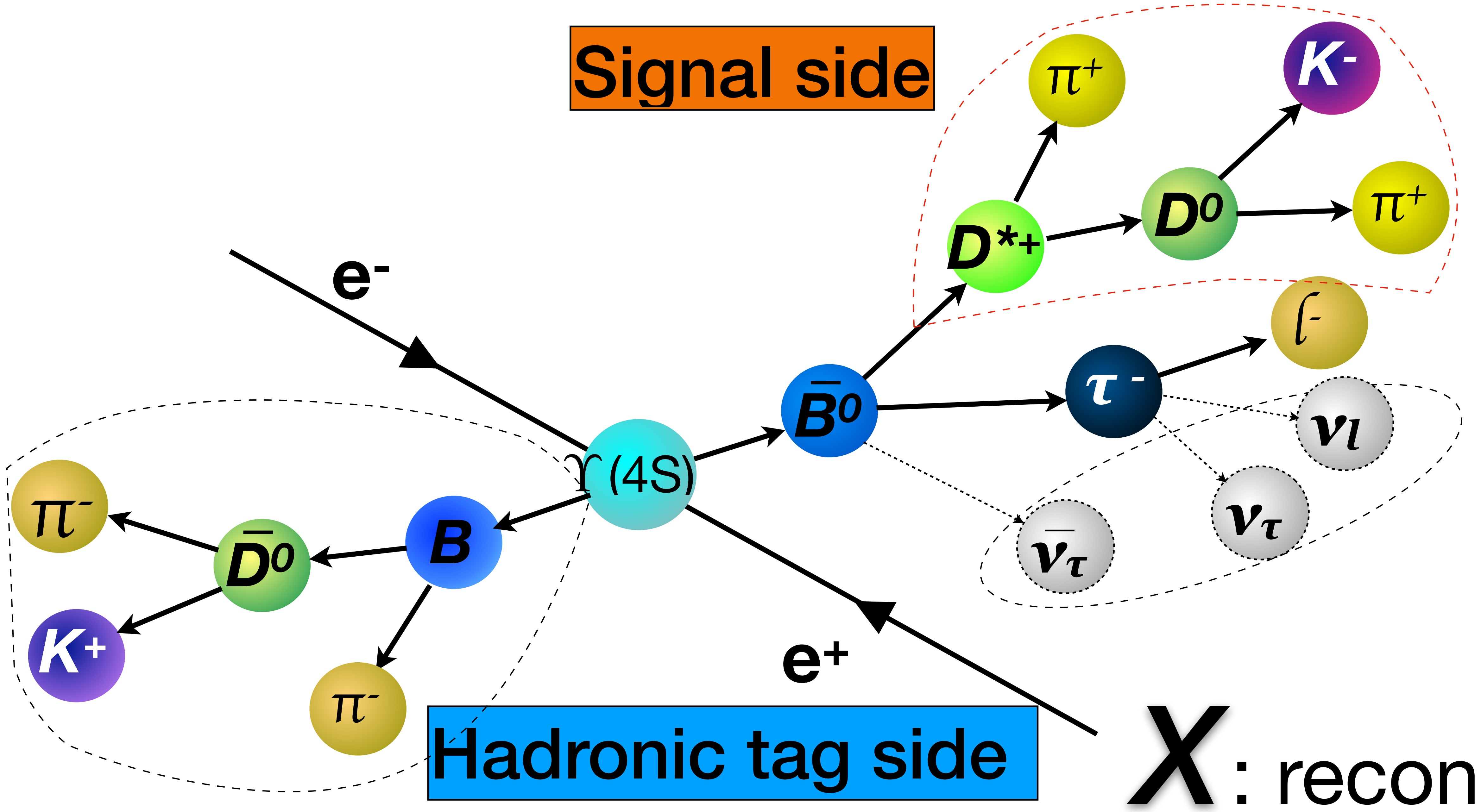


K_L/μ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

- Features:
  - Near-hermetic detector
  - Vertexing and tracking: σ vertex ~ 15μm, CDC spatial res. 100μm $\sigma(P_T)/P_T$ ~ 0.4%
  - Good at measuring neutrals, π^0, γ, K_L… $\sigma(E)/E$ ~ 2-4%

Hadronic tagging methods

- The $B\bar{B}$ pairs are produced near threshold
- *B* tagging is necessary to measure $B \to X / D^* \tau \nu$, $B \to X / D^* l \nu$ ($\nu \geq 2$) simultaneously
- Hadronic tag
  - Fully reconstruct $B \to D^{(*)}(/J/\psi/\Lambda)X$
  - Tagging efficiency 0.2~0.4%
  - less background



X: reconstruct other particles than a lepton as *X* on signal side

- Fully reconstruct one of the *B* mesons (*B* tag), possible to measure momentum of other *B* meson (*B* signal)
- Indirectly measure missing momentum of neutrinos in signal *B* decays
- $M^2_{miss} = (p_{beam} - p_{Btag} - p_{D^{(*)}} - p_l)^2$
- E_{ECL} unassigned neutral energy in the calorimeter $E_{ECL} = \sum_i E_i^{\gamma}$

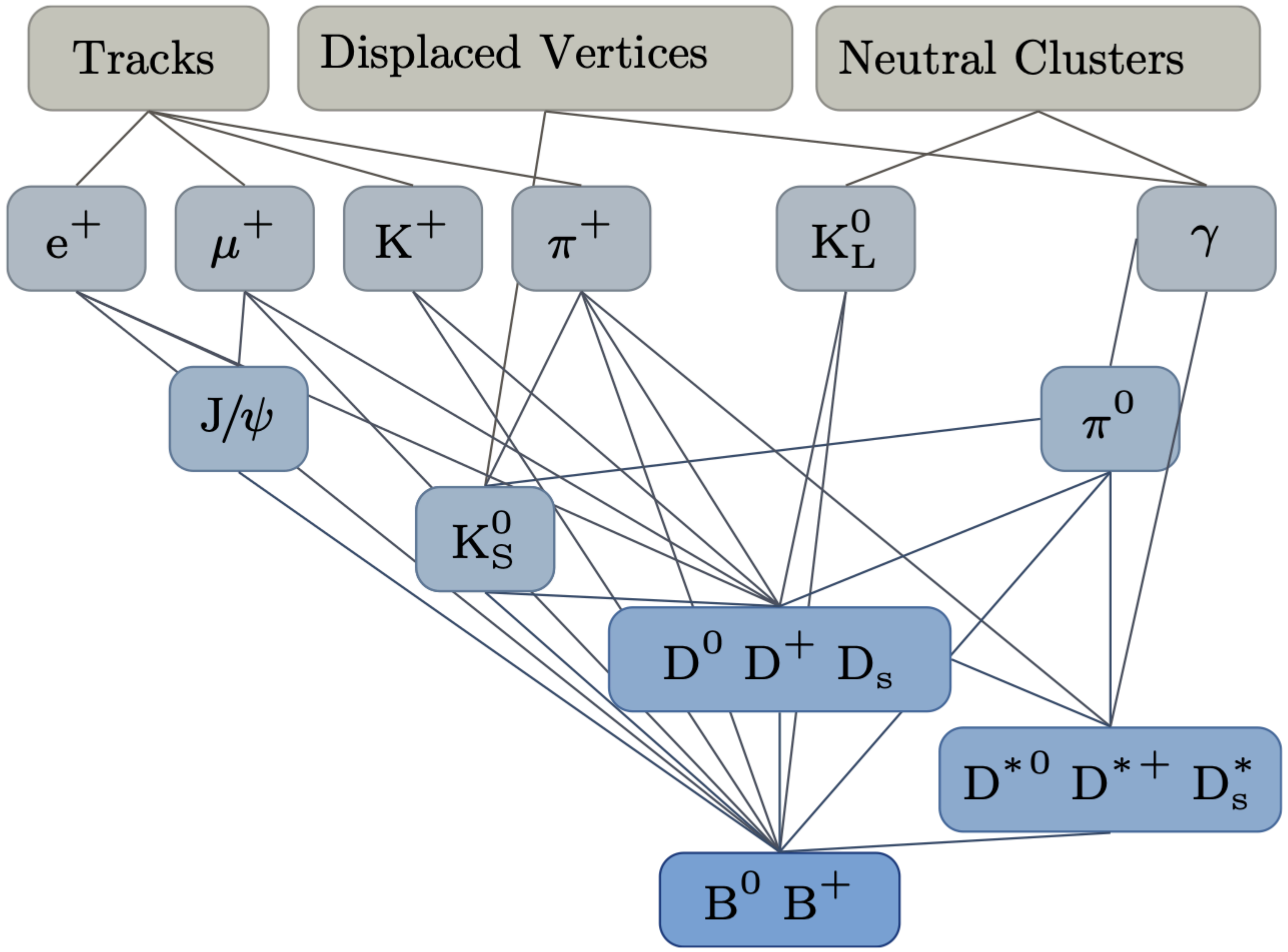
Hadronic tag reconstruction at Belle II

- Hadronic tagging reconstruction: Full Event Interpretation (FEI) trained 200 Boost Decision Tree (BDT) to reconstruct ~100 decay channels, ~10,000 *B* decay chains
  - ε=0.30% for $B^{\pm}$
  - ε=0.23% for B^{0}

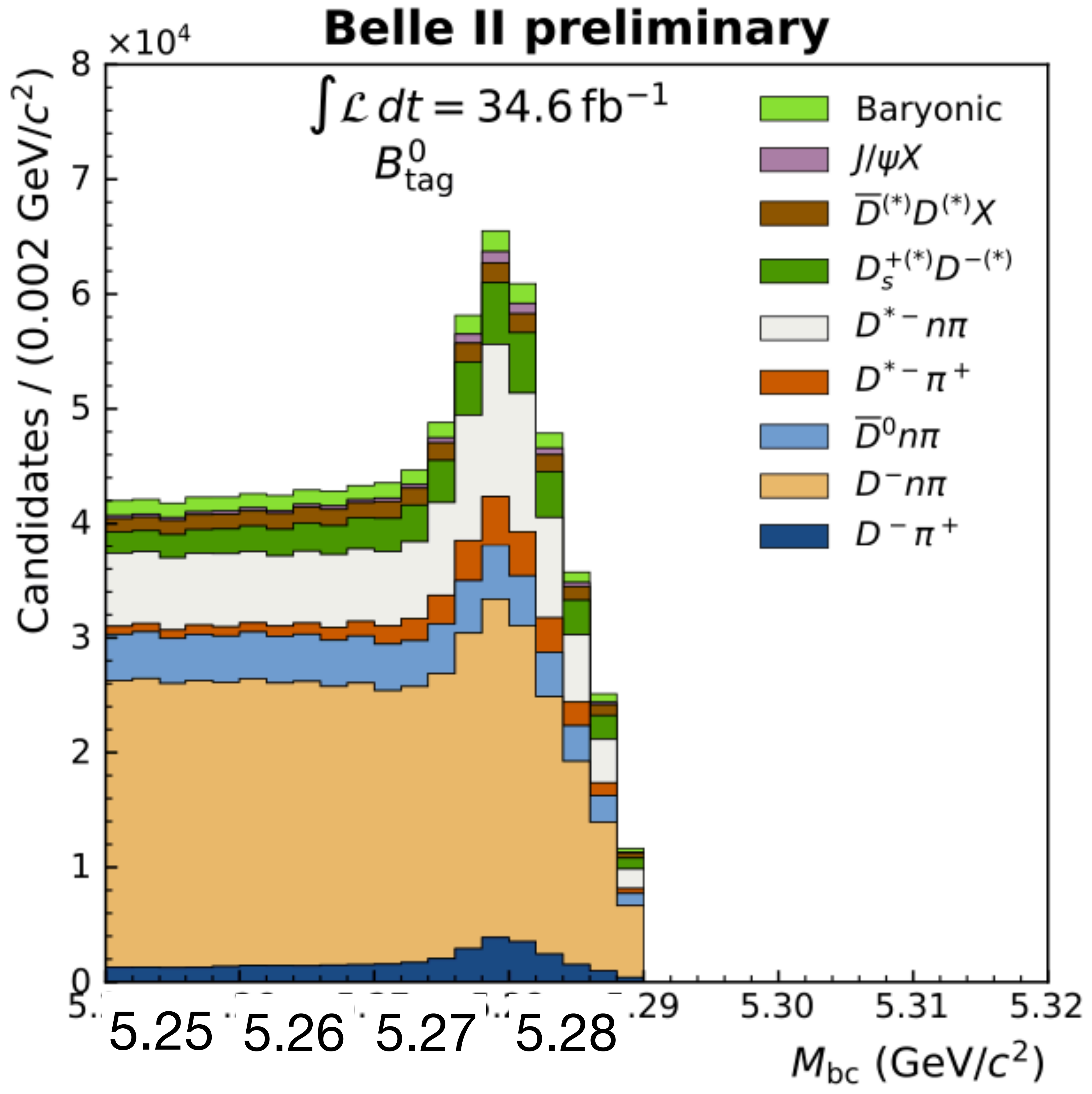
10-30% increased

- ε=0.28% for $B^{\pm}$ @Belle
- ε=0.18% for B^{0} @Belle

Comp. and Soft. For Big Sci. 3, 6 (2019)



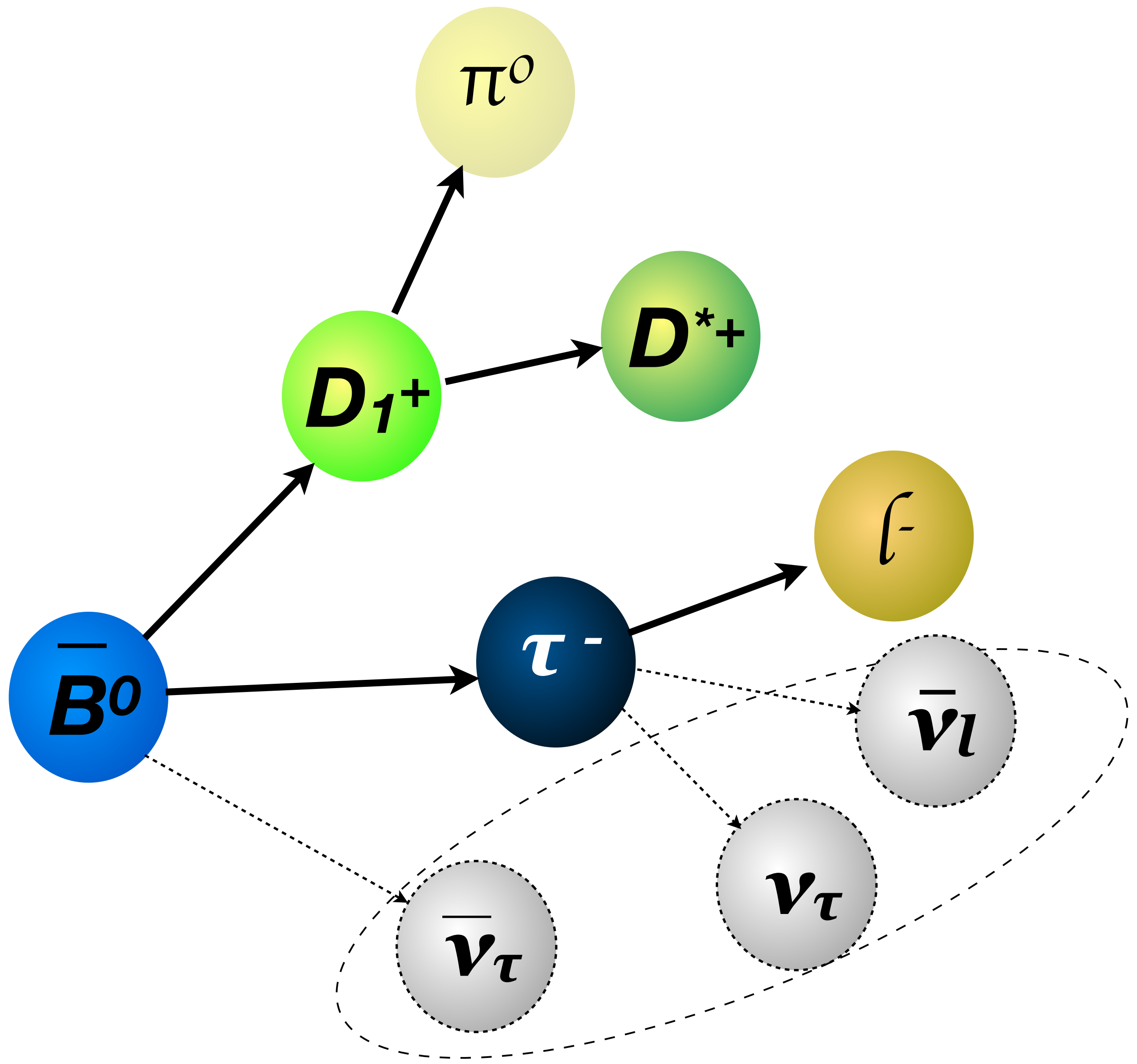
arXiv:2008.06096



$$m_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2}$$

Signal B reconstruction

- Reconstruct $B\to D^*\tau\nu$ and $B\to D^*l\nu$ with same selections
- τ lepton reconstruct with ℓ (e, μ)$\nu\nu$
- D/D^* meson reconstruct with $K^{\pm}$, $\pi^{\pm}$, K_S, π^0
- Both neutral and charged $B^{\pm}/B^0$ mesons reconstruct with D^{*+}/D^{*0} and τ/ℓ = (e, μ)

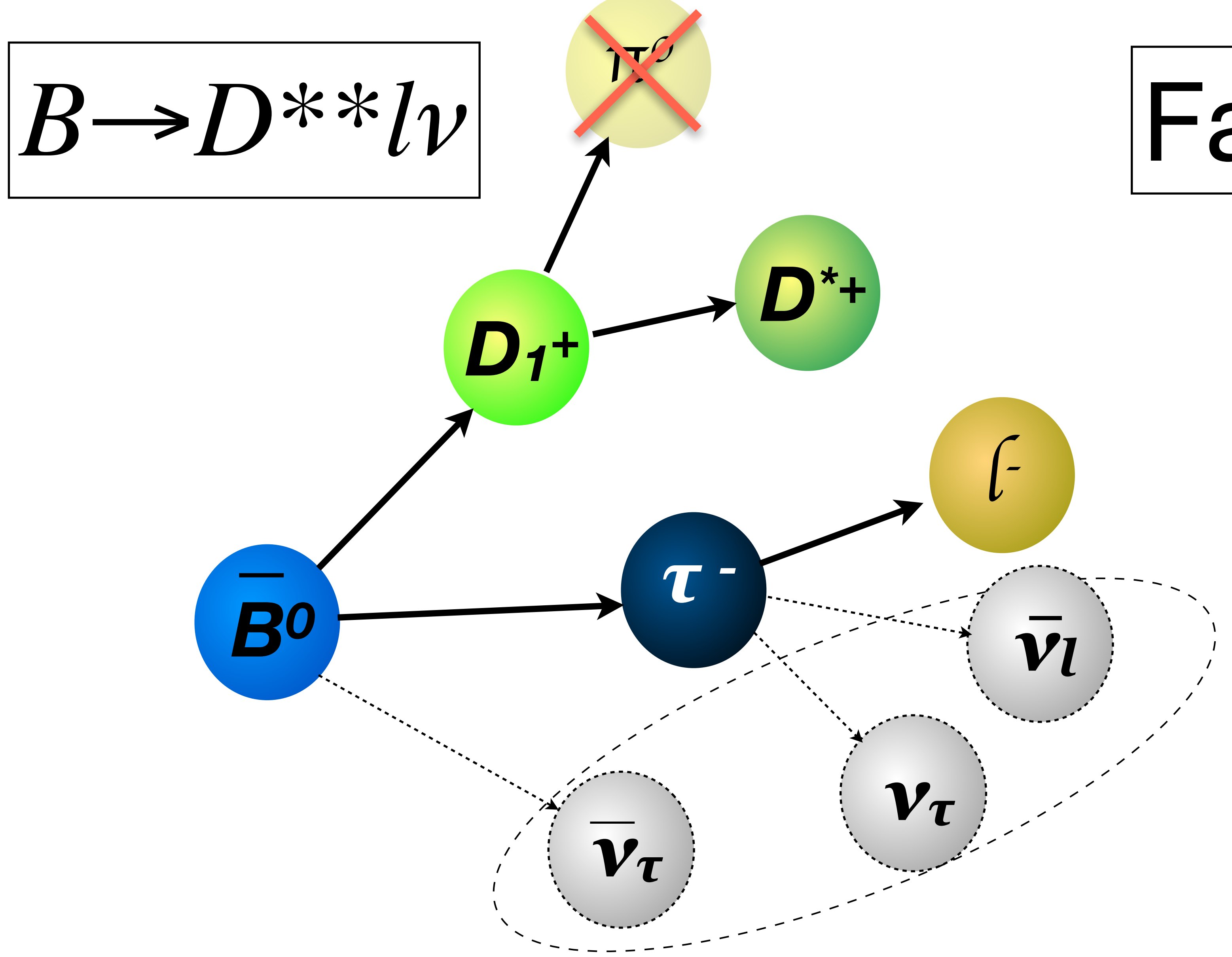


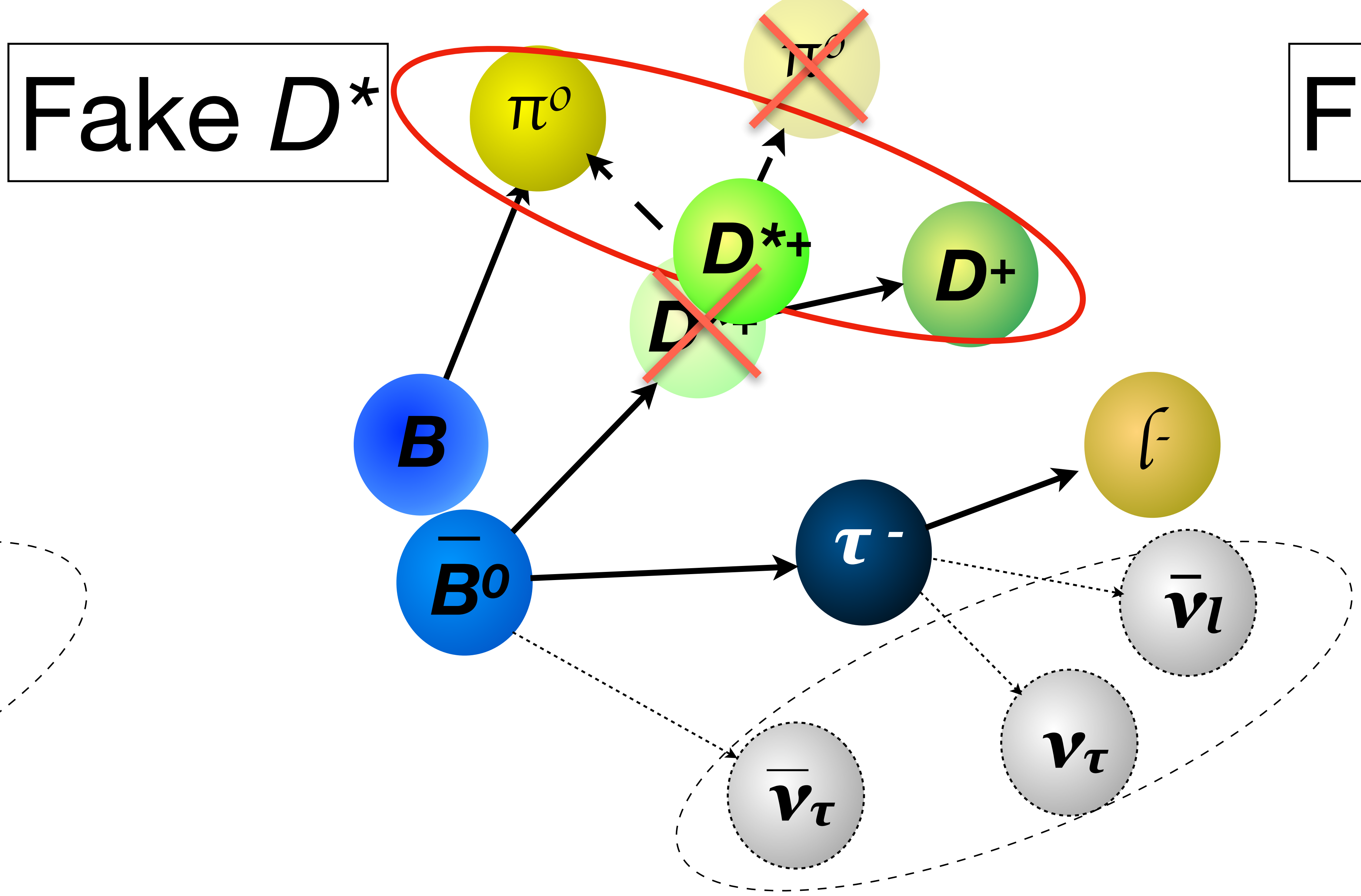
$D^{*+} \to D^0\pi^+/D^+\pi^0$	$\mathcal{B}$~98%
$D^{*0} \to D^0\pi^0$	$\mathcal{B}$~65%
Eight D^0 modes	$\mathcal{B}$~36%
Three D^+ modes	$\mathcal{B}$~12%

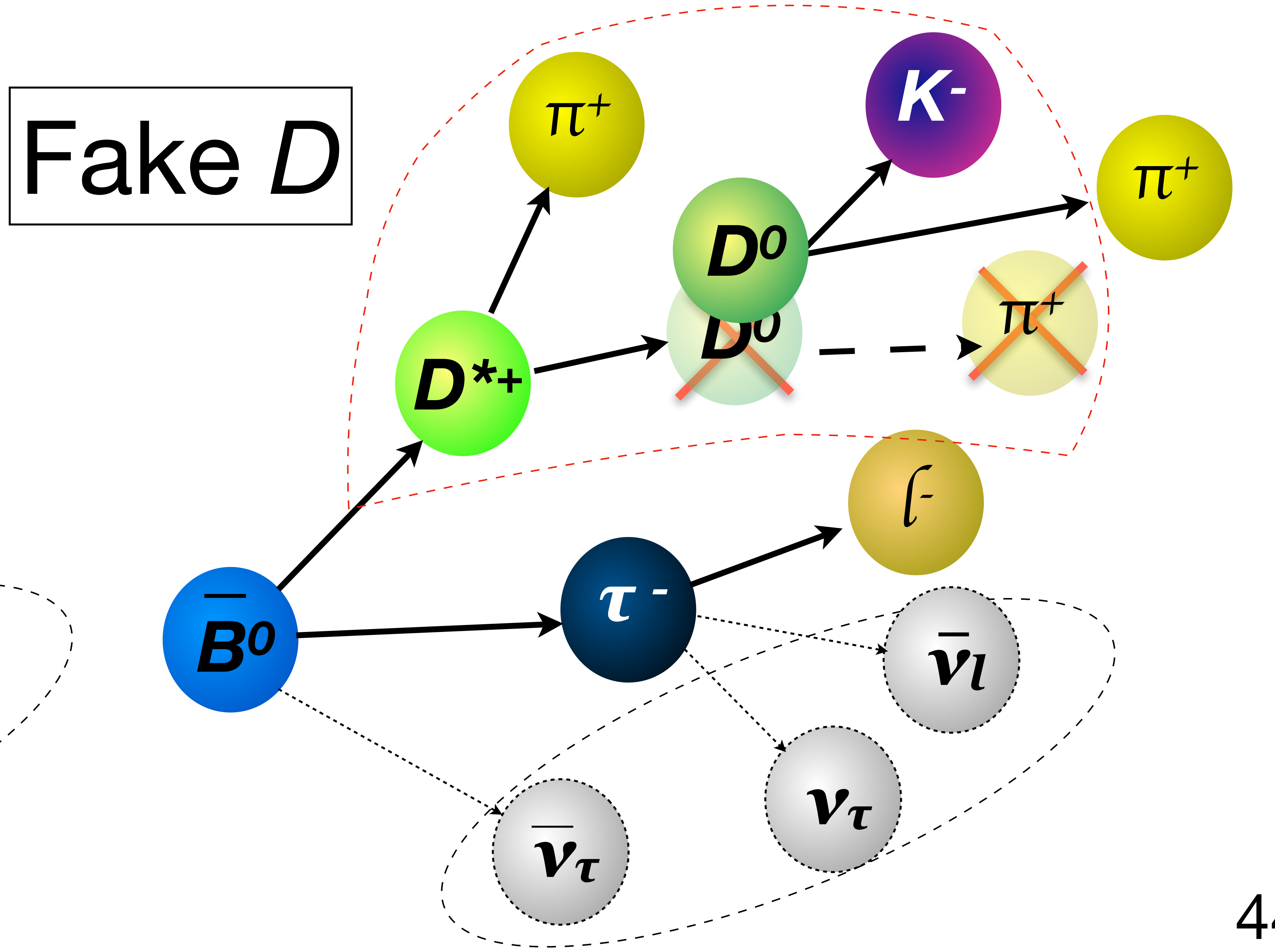
Dominant backgrounds

- Fraction of survived *B* candidates in each category after event selections are estimated based on Belle II MC simulation

B condidates	$B \to D^{*}\tau\nu$	$B \to D^{*}l\nu$	**Background Truth $D^{(*)}$** $B \to D^{**}l\nu$, $B \to D^{(*)}X$, B^0<->$B^{\pm}$, …	**Background Fake $D^{(*)}$**
B^0	2.7%	65.5%	12.5%	19.2%
$B^{\pm}$	1.7%	34.7%	5.9%	57.8%

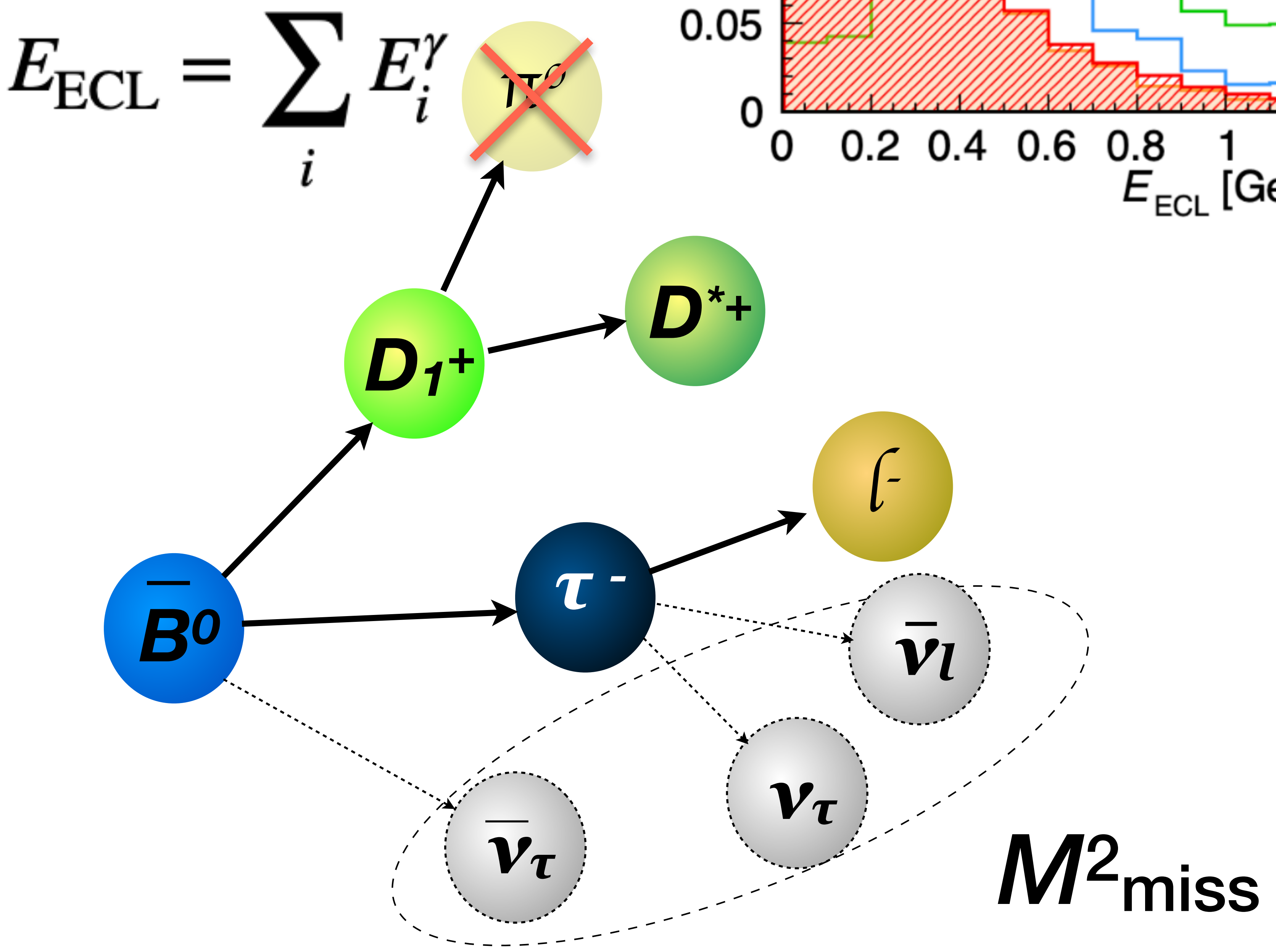


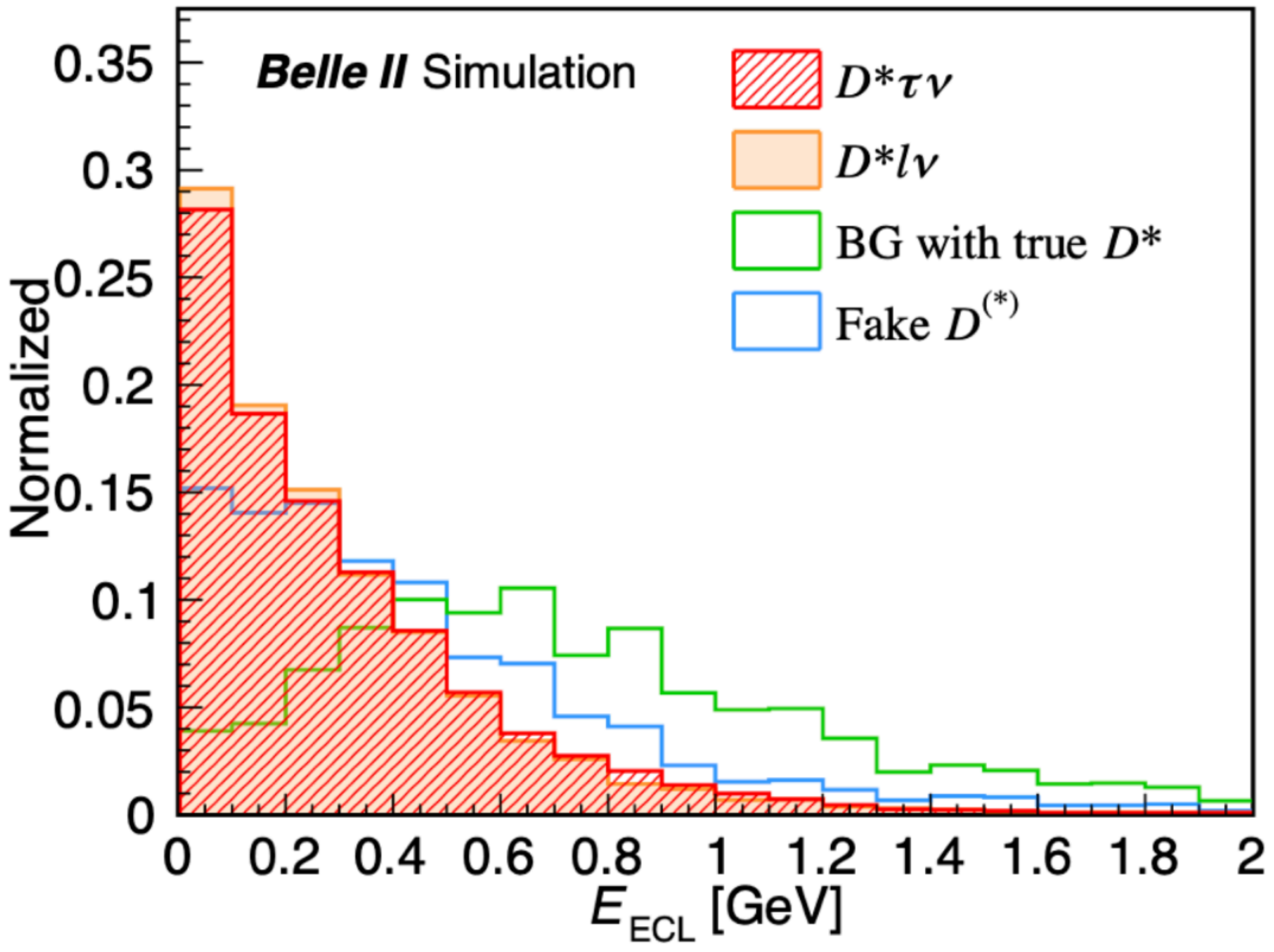


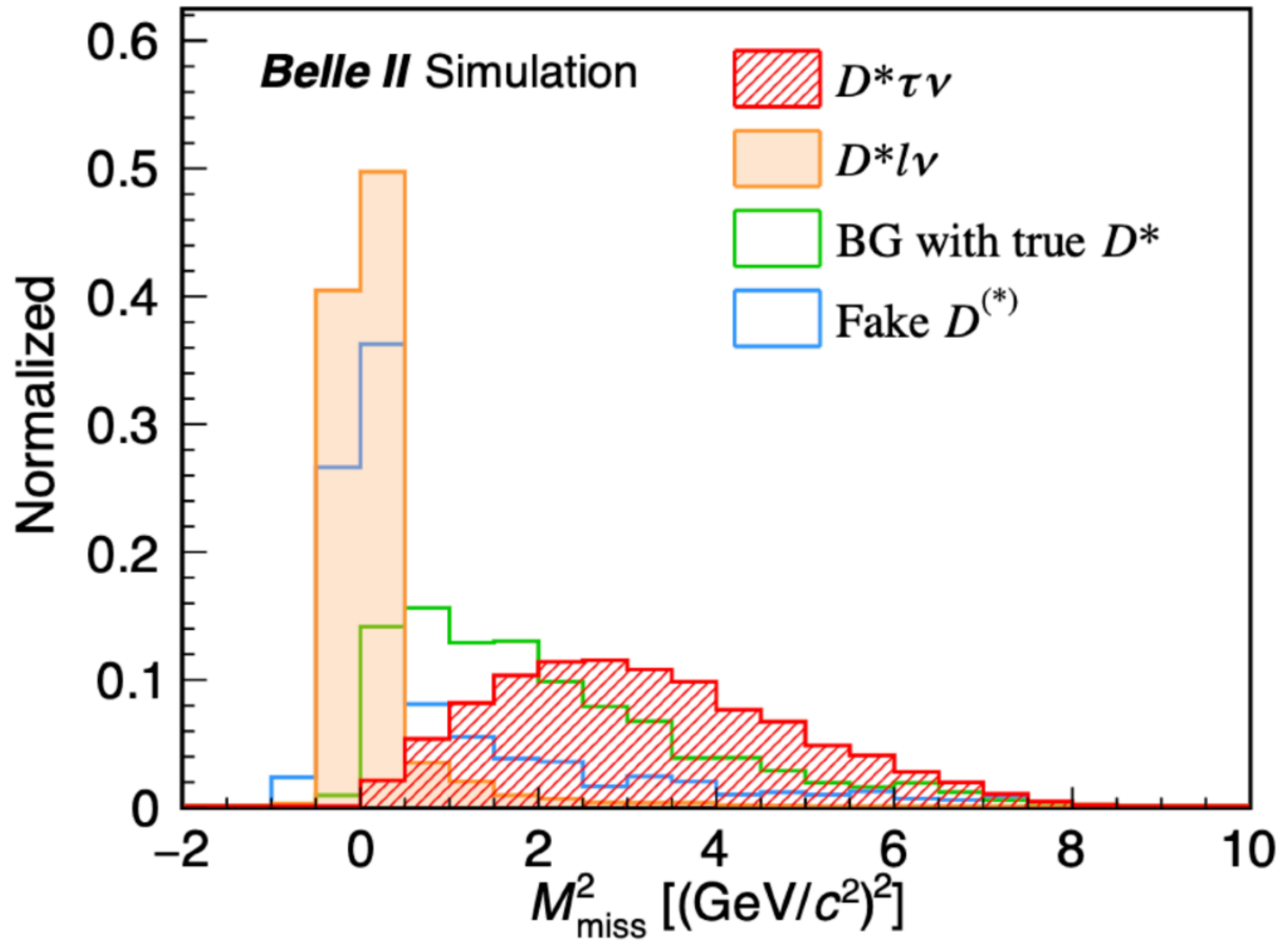


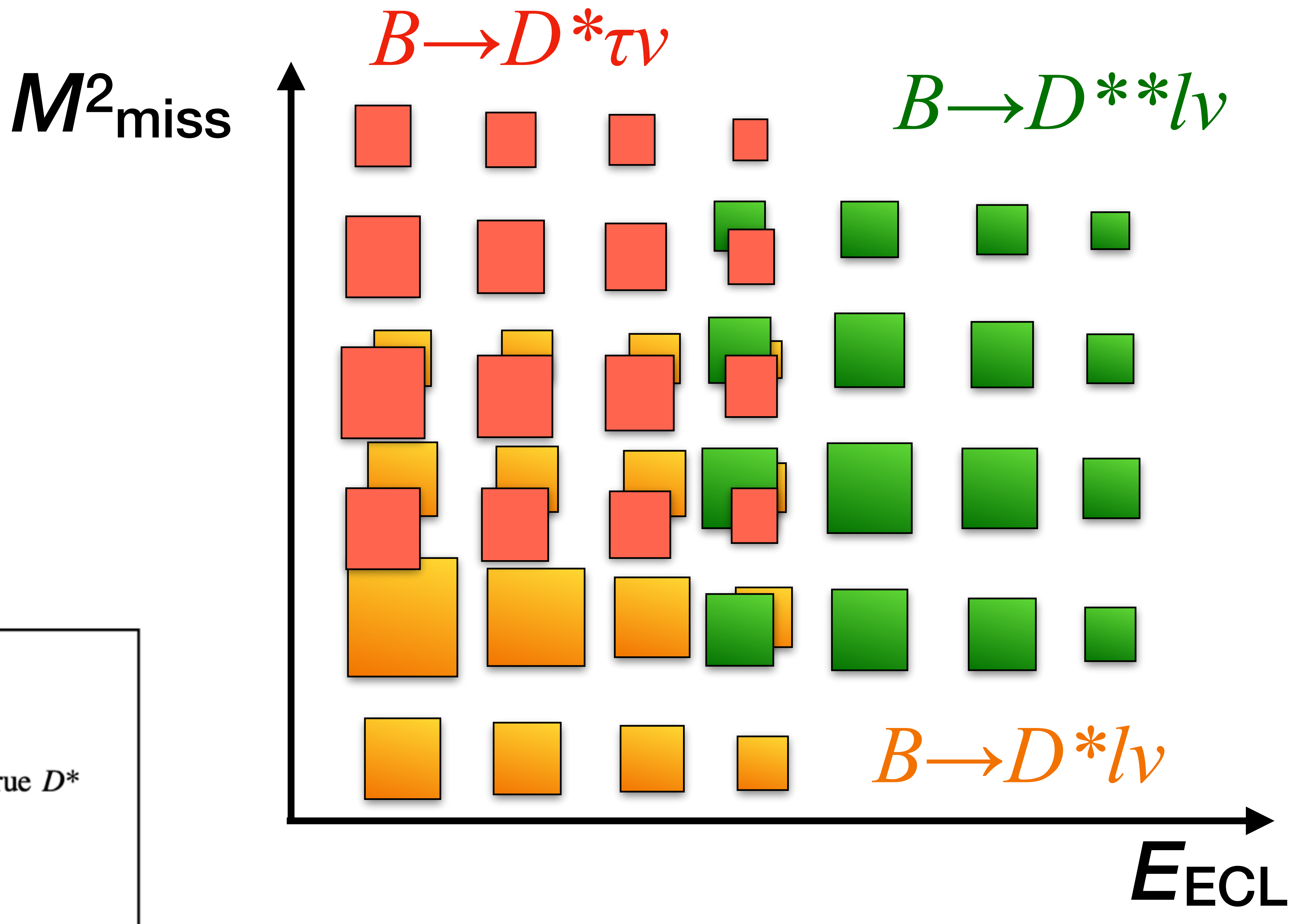
Fitting methodology and variables

- Extracting $B\to D^*\tau\nu$, $B\to D^*l\nu$ yields by a two-dimensional simultaneously fit
  - $M^2_{\rm miss} = (p_{\rm beam} - p_{B\rm tag} - p_{D(*)} - p_l)^2$
  - $E_{\rm ECL}$ unassigned neutral energy in the calorimeter $E_{\rm ECL} = \sum_i E_i^\gamma$

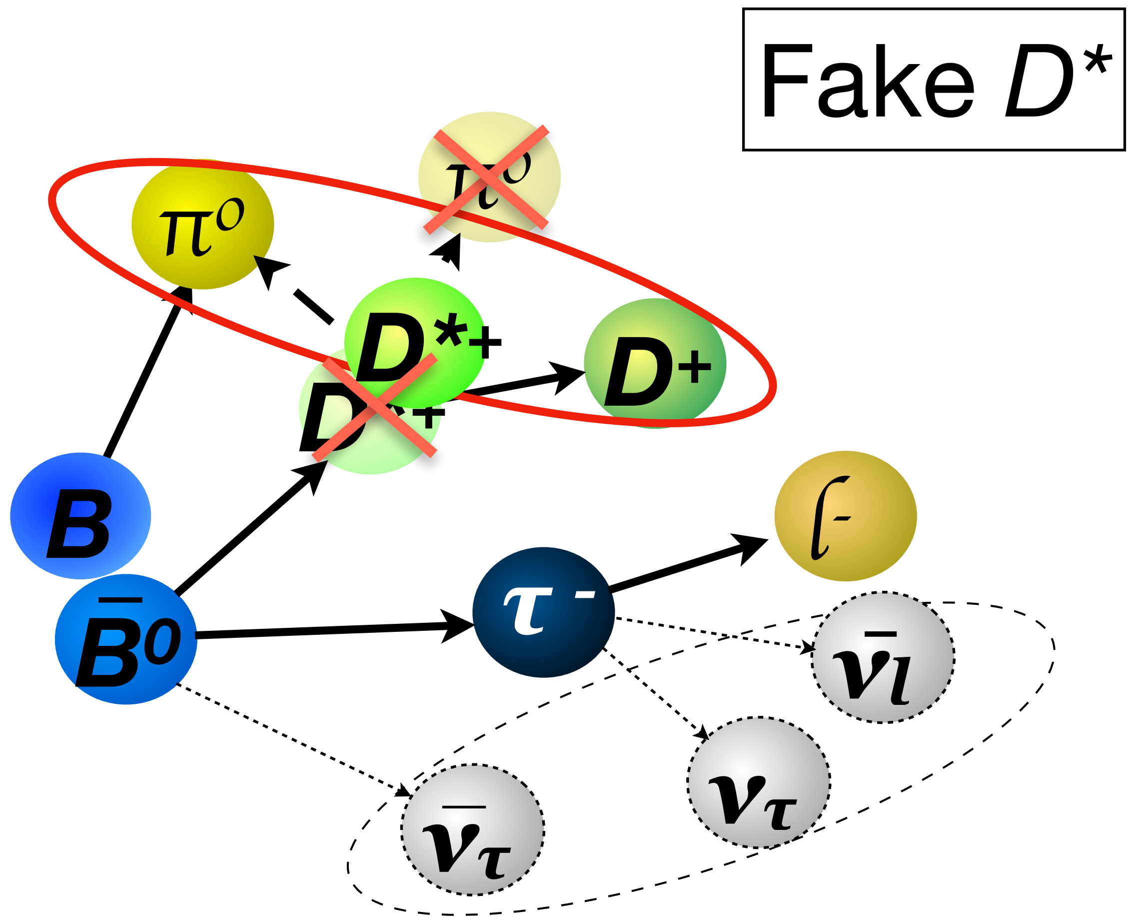


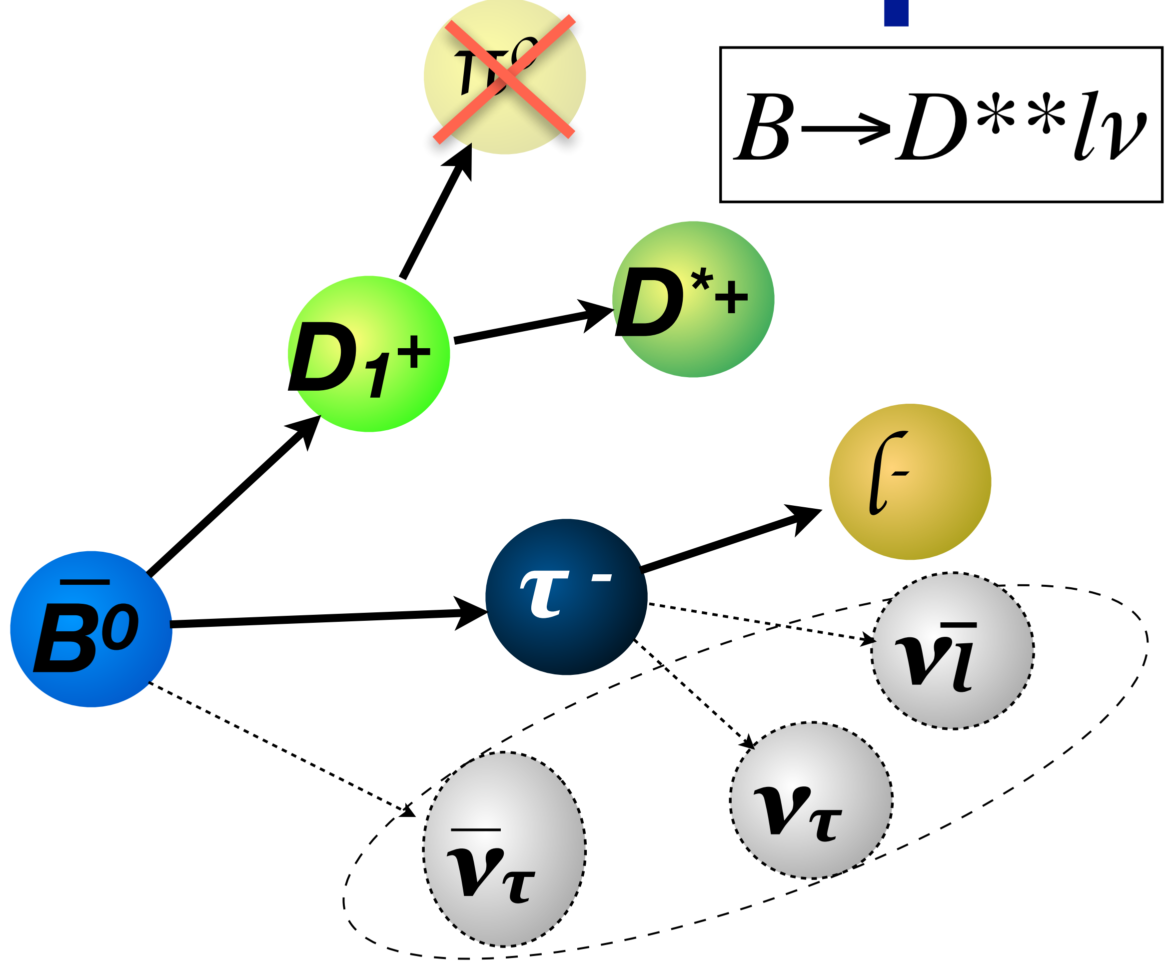


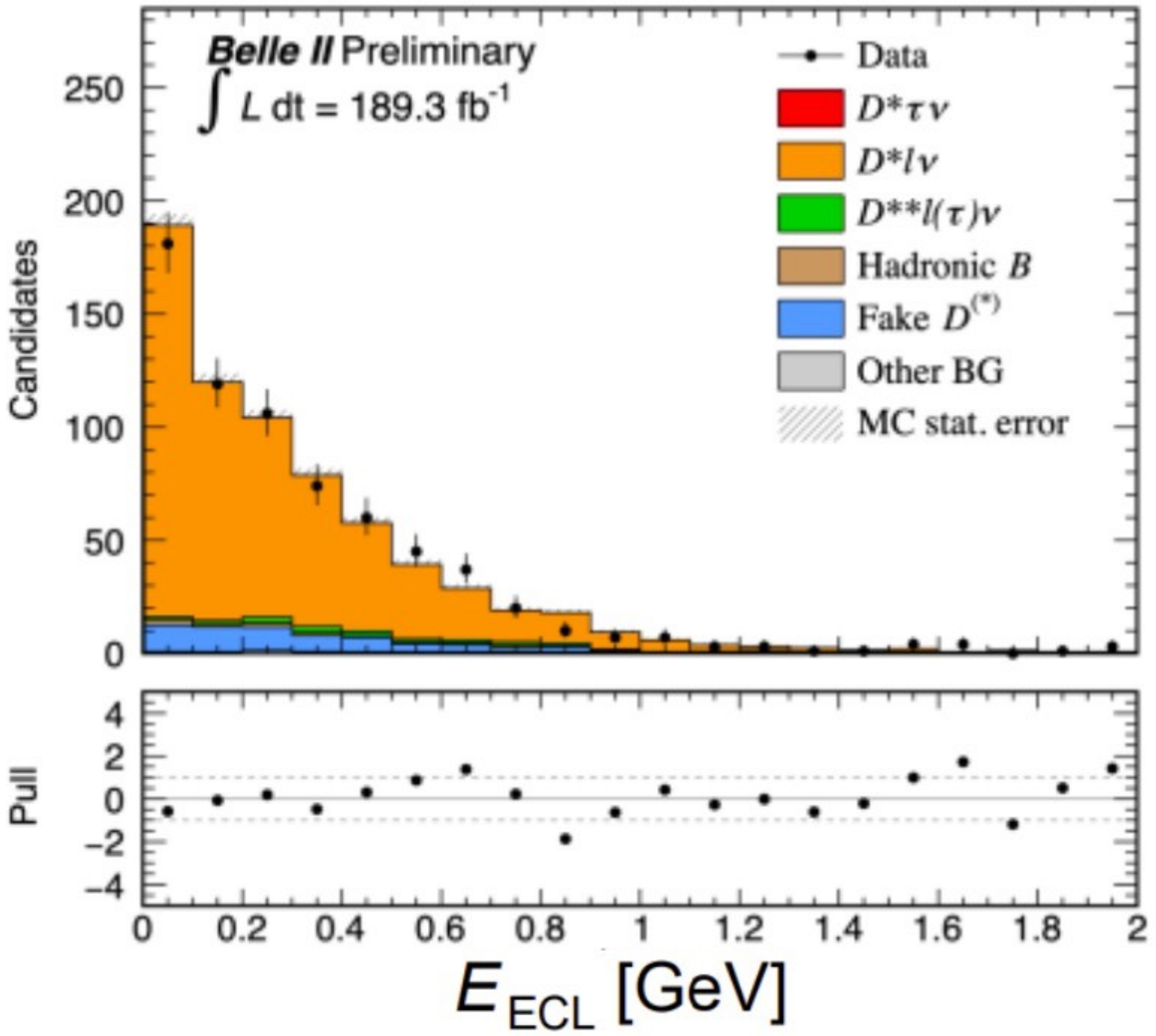




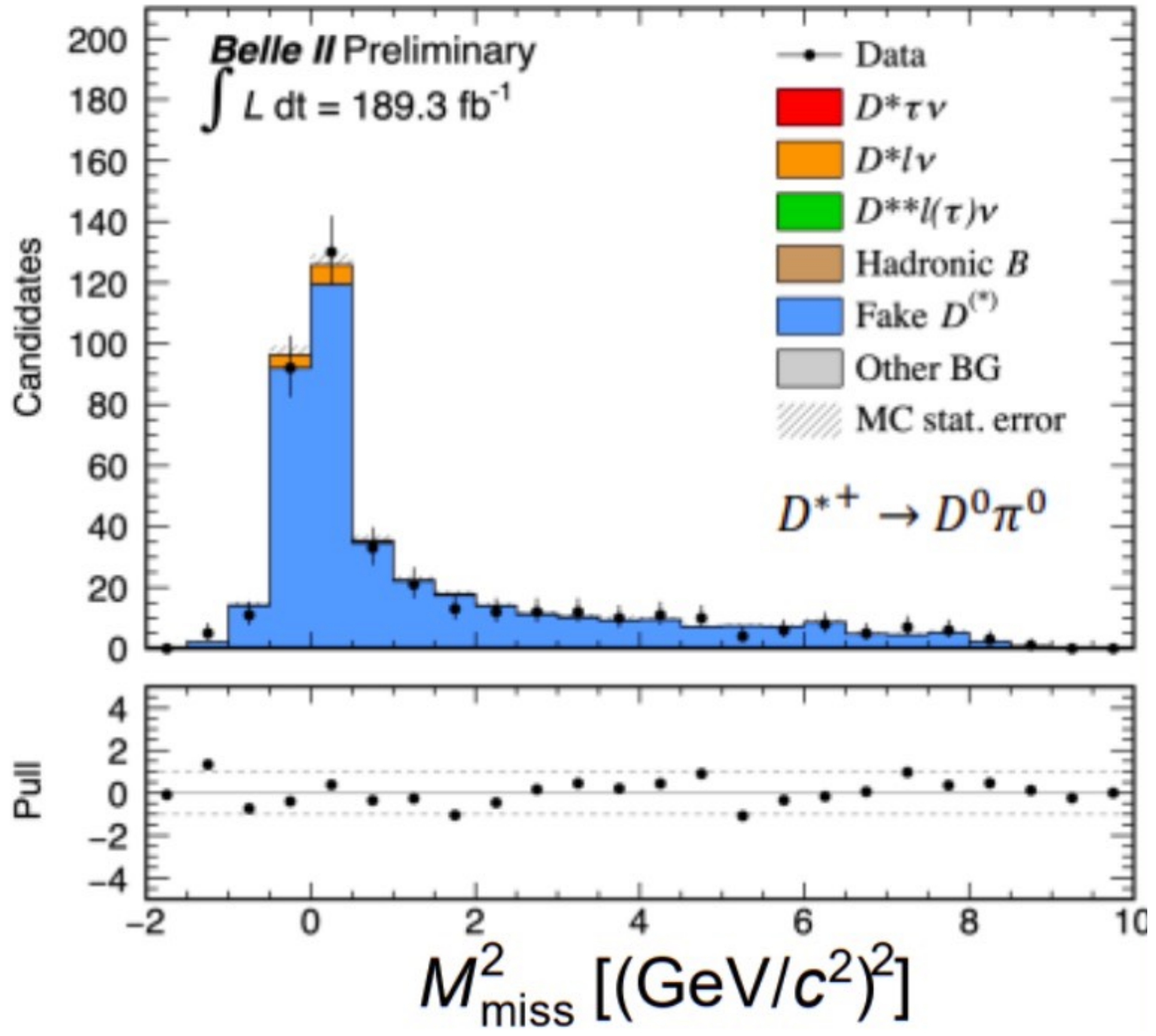
Dominant backgrounds and control samples



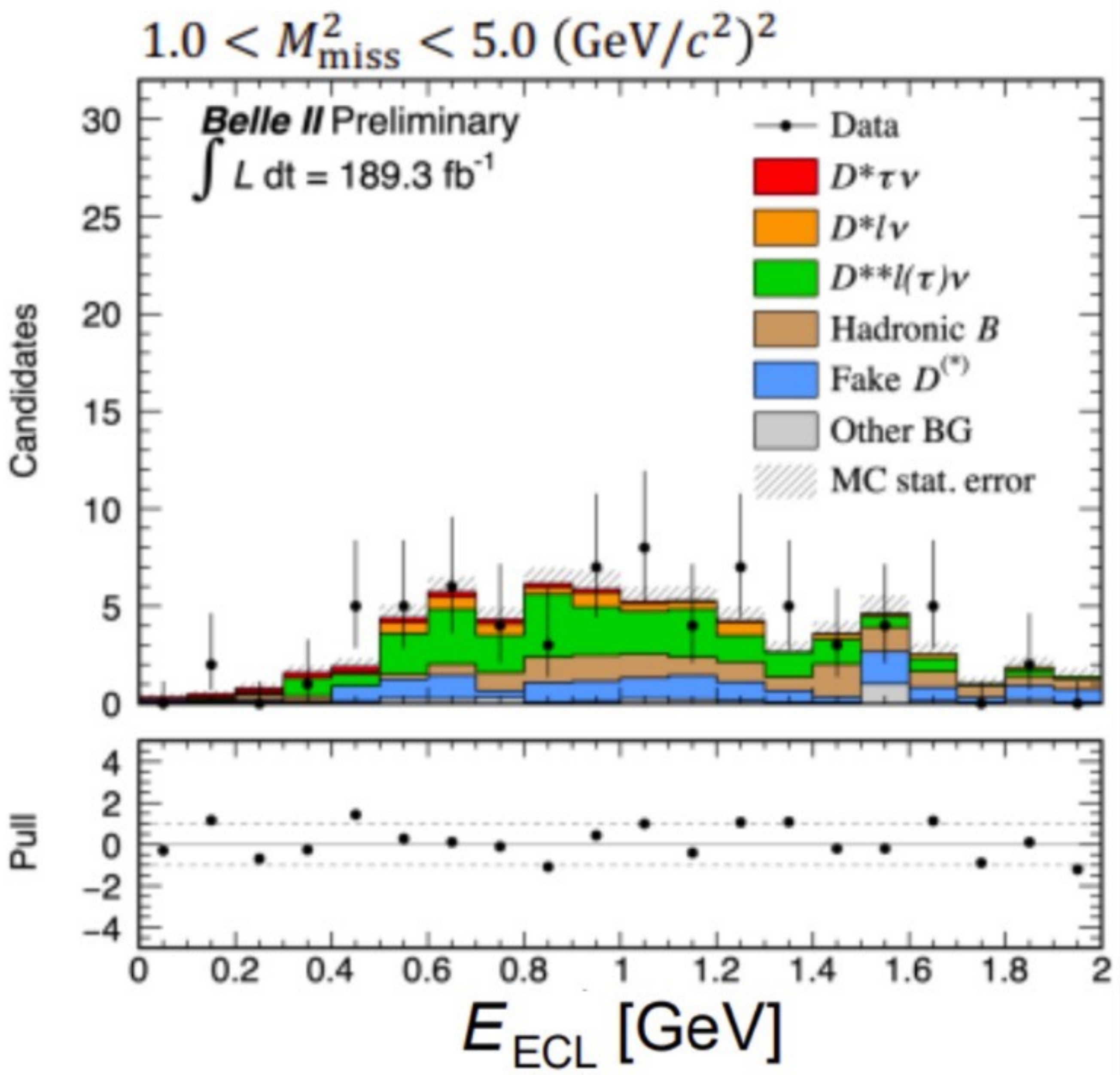




$q^2 < 3.5$ GeV sideband:
validate E_{ECL} modeling



$m(D\pi)$ - $m(D^*)$ sideband:
validate fake D^* modeling



Reconstruct $D^*\pi^0 l\nu$
validate D^{**} modeling

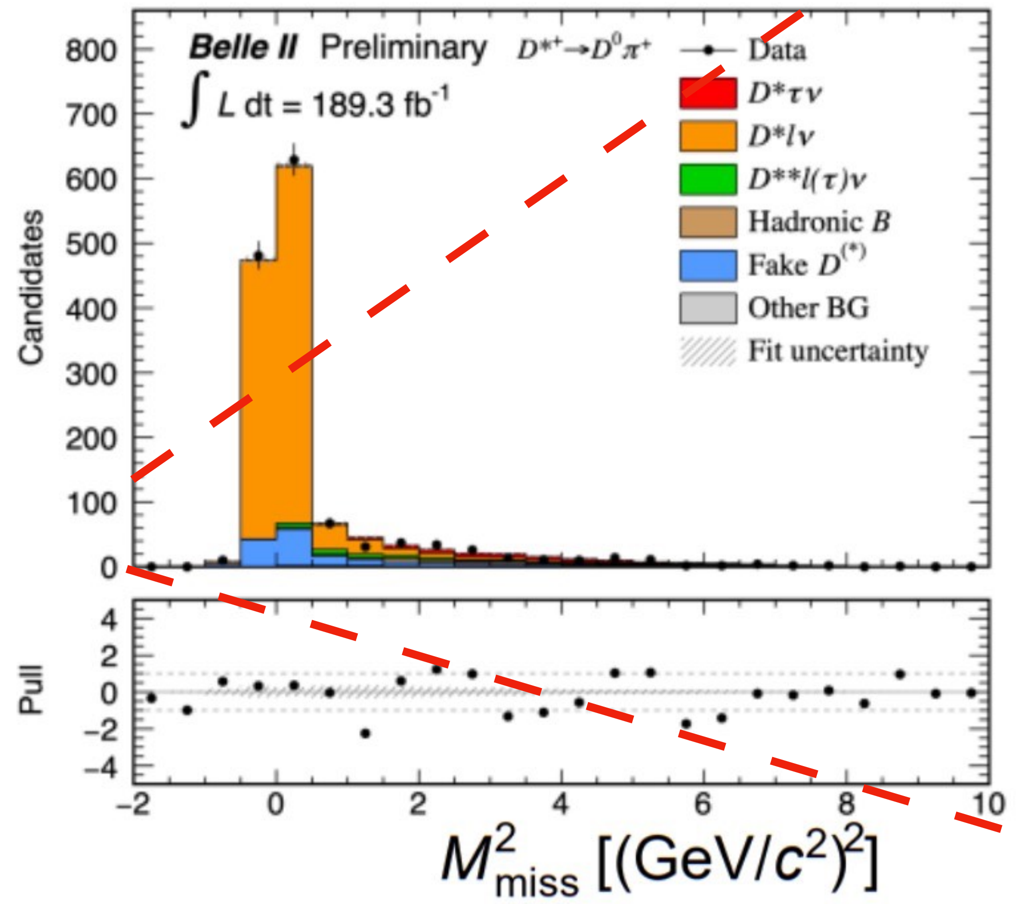
$R_{\tau/\ell}(D^*)$ results

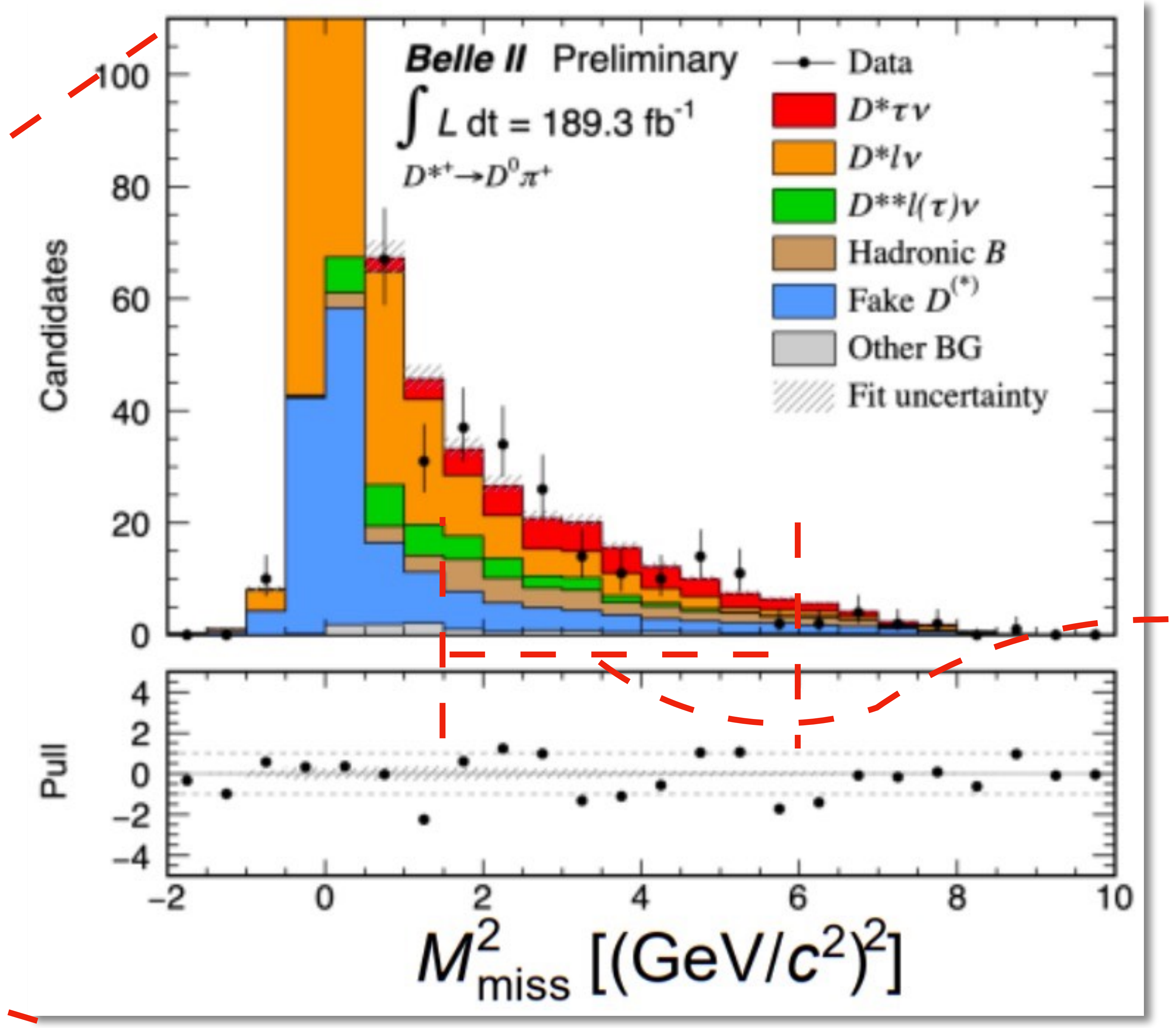
- Similarly sensitivity as Belle 15' result @ 711 fb^{-1} with only 189 fb^{-1}
- Belle II first result for $R(D^*)$

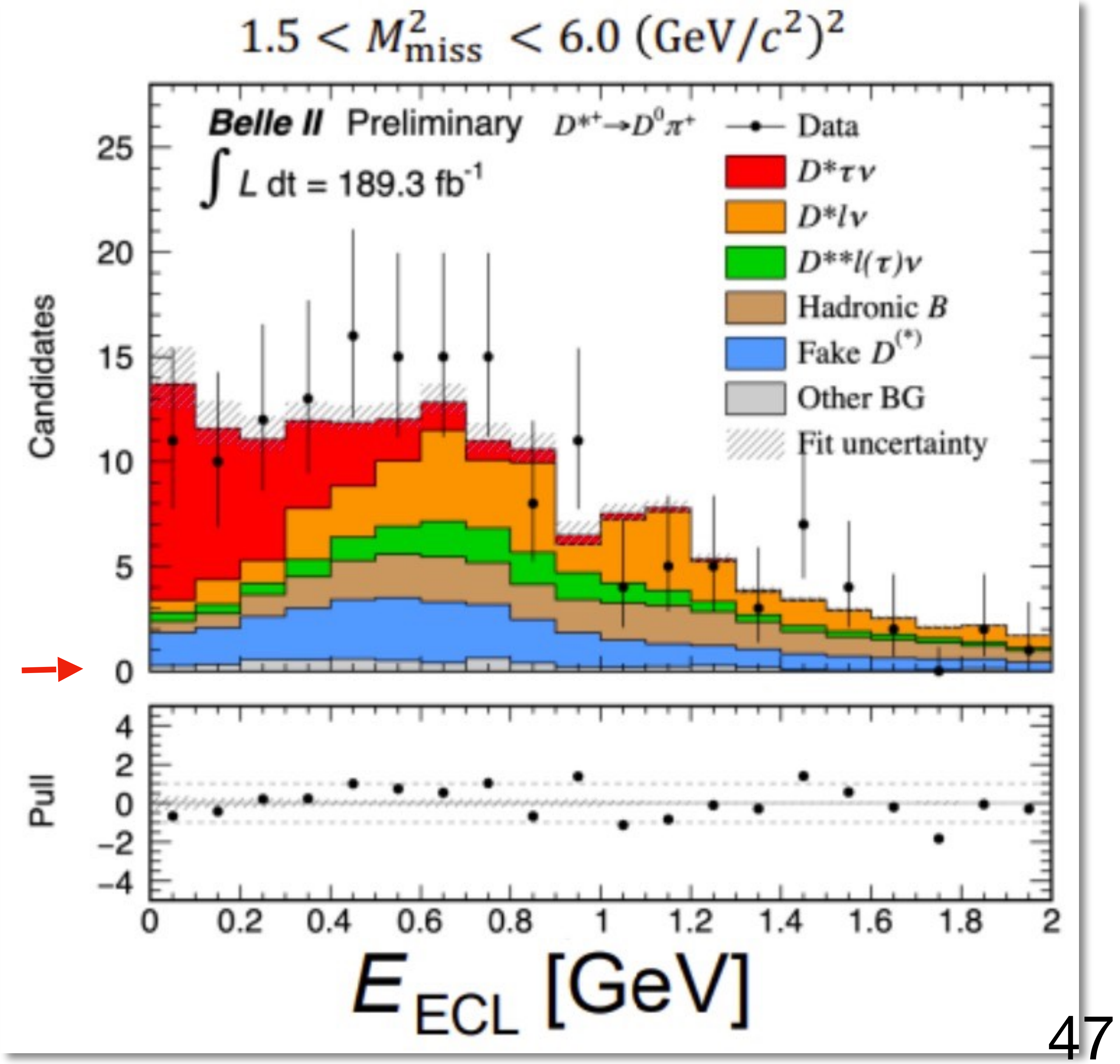
$$R(D^*_{\tau/\ell}) = 0.262\ ^{+0.041}_{-0.039}\ (\text{stat})\ ^{+0.035}_{-0.032}\ (\text{syst})$$

- Consistent with
  SM: 0.254 ± 0.005,
  HFLAV24: 0.287 ± 0.012
- SM vs. experimental average deviation: 3.2σ → 3.3σ

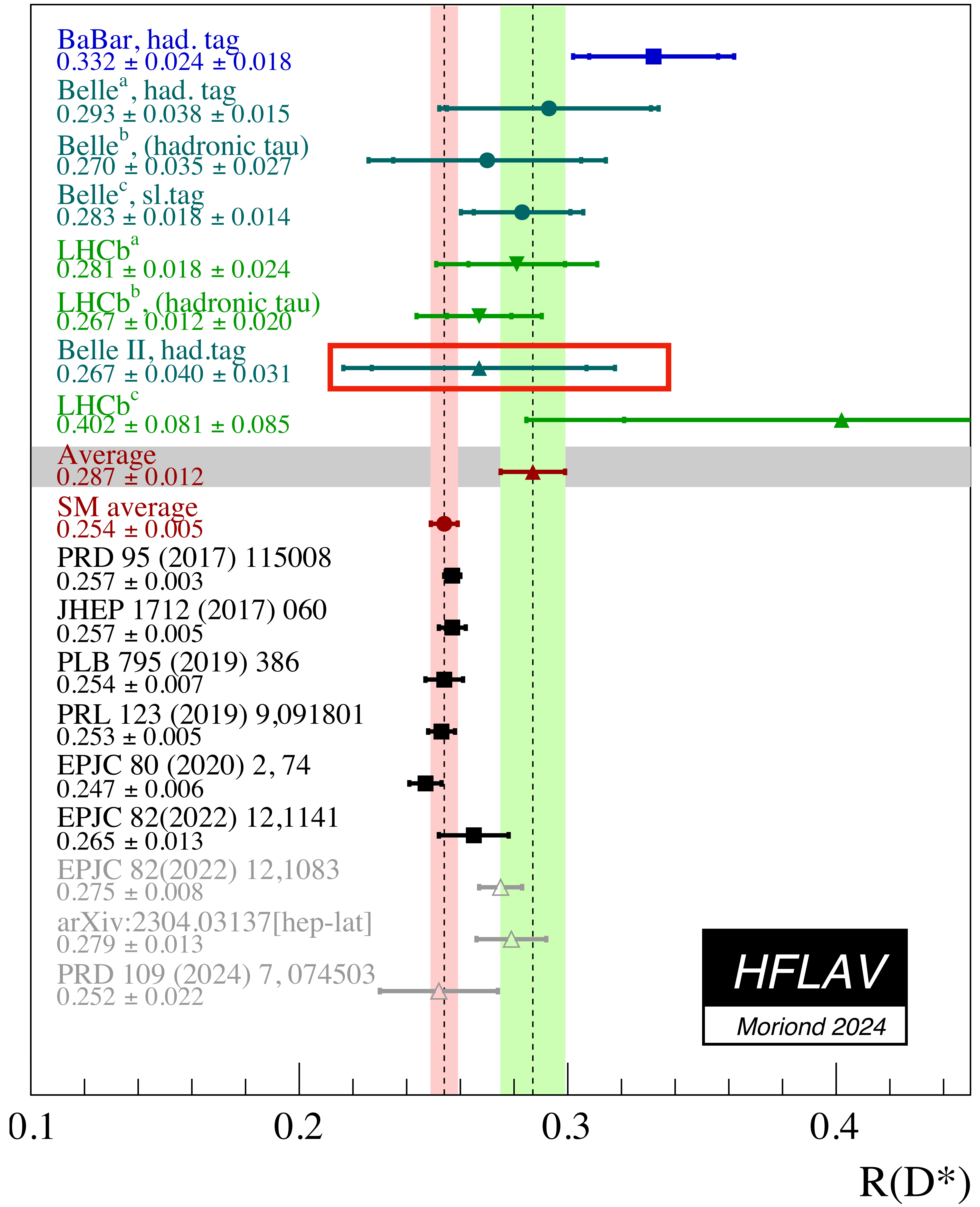
Source	Uncertainty
Statistical uncertainty	+15.4% -14.6%
E_{ECL} PDF shape	+9.1% -8.3%
MC statistics	±7.5%
$B \to D^{**} l \nu$ modeling	+4.8% -3.5%

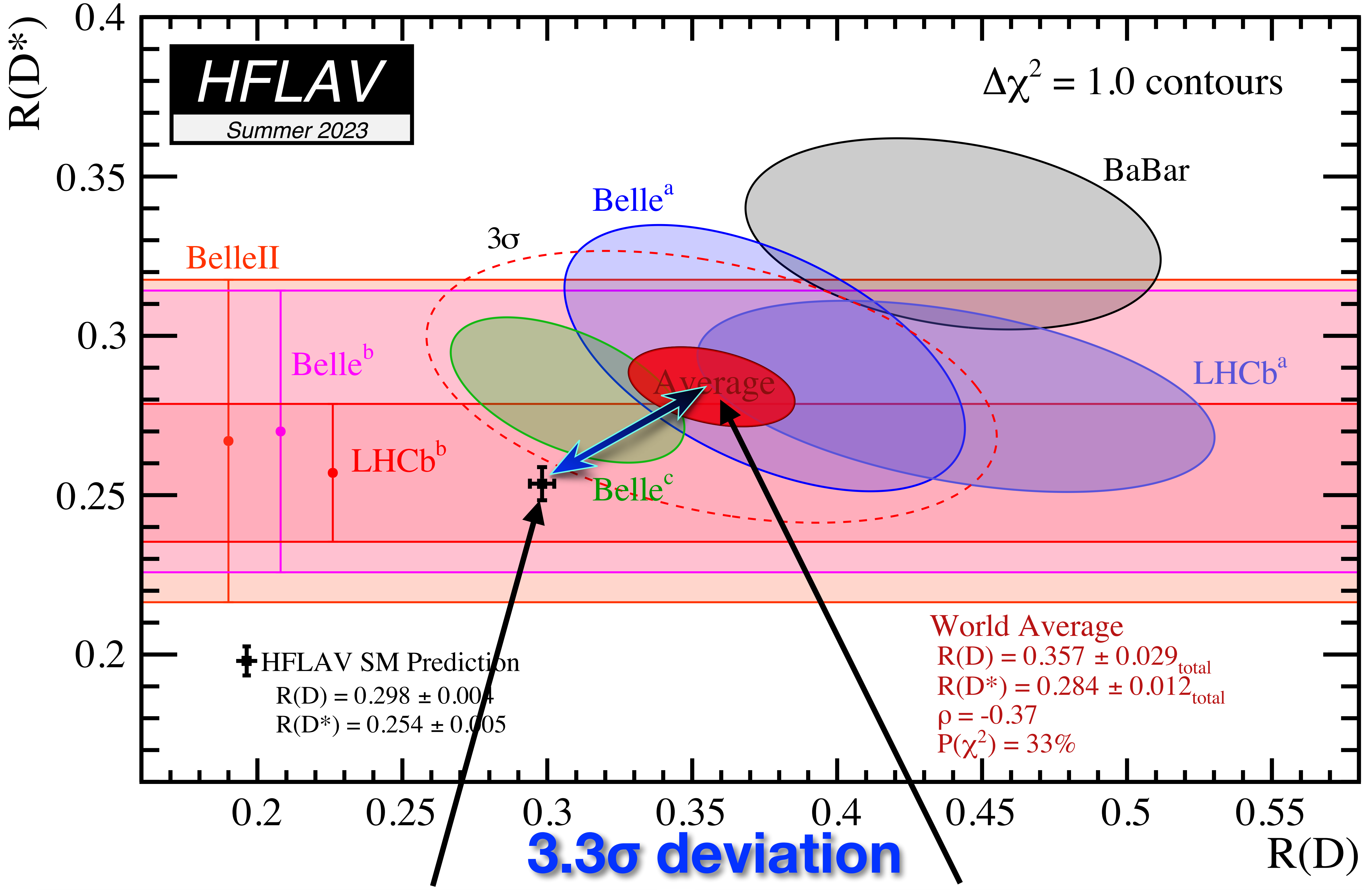






"*B* anomaly" in semileptonic decays





Standard Model prediction

Experimental average results

New Physics scenarios with Effective Field Theory

- New physics contribution to $R(D^{(*)})$ are tested with Wilson operators

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_L}\mathcal{O}_{S_L} + C_{S_R}\mathcal{O}_{S_R} + C_T\mathcal{O}_T]$$

$\mathcal{O}_{V_L}$, $\mathcal{O}_{V_R}$: Left-, right-handed vector operators
$\mathcal{O}_{S_L}$, $\mathcal{O}_{S_R}$: Left-, right-handed scalar operators
$\mathcal{O}_T$: Tensor vector operators

C_X: Willson coefficient for a X operator

Refer to: PRD 110, 075005 (2024)

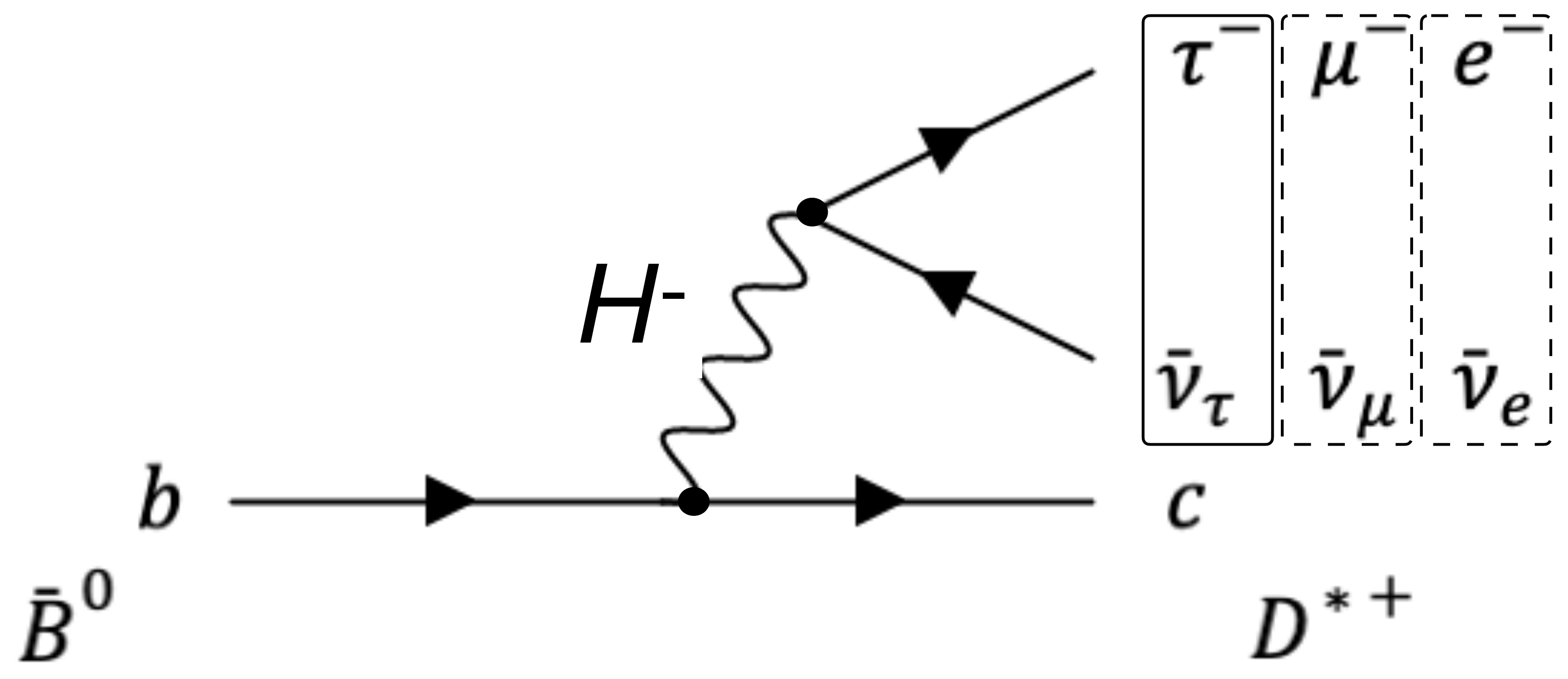
$$\frac{R_{D^*}}{R_{D^*}^{\text{SM}}} = |1 + C_{V_L}|^2 + |C_{V_R}|^2 + 0.04|C_{S_L} - C_{S_R}|^2 + 16.0|C_T|^2$$
$$- 1.83\text{Re}[(1 + C_{V_L})C_{V_R}^*] - 0.11\text{Re}[(1 + C_{V_L} - C_{V_R})(C_{S_L}^* - C_{S_R}^*)]$$
$$- 5.17\text{Re}[(1 + C_{V_L})C_T^*] + 6.60\text{Re}[C_{V_R}C_T^*],$$

- Exp. average to constrain Wilson coefficients

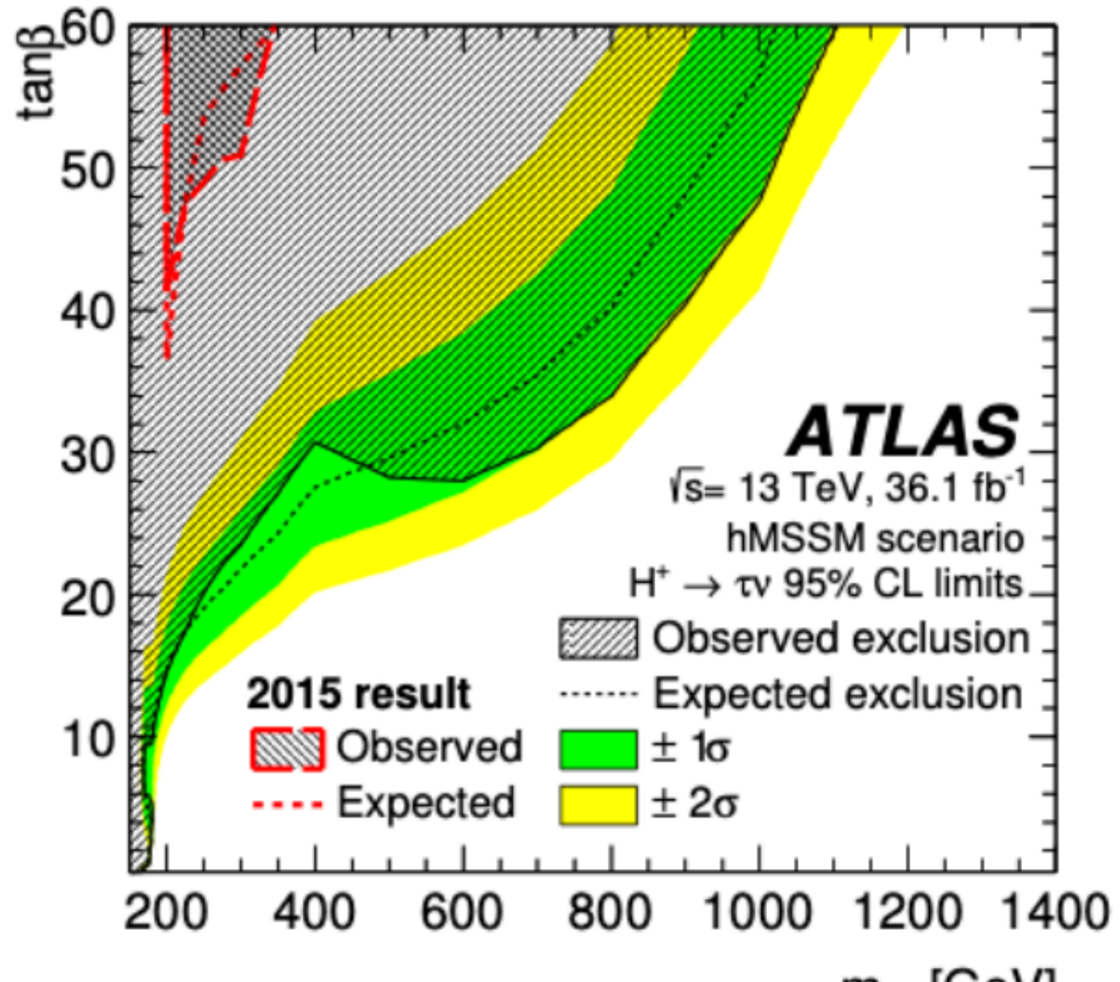
	$R(D)$	$R(D^*)$
Exp. average	0.356 ± 0.029	0.284 ± 0.013
SM	0.298 ± 0.004	0.254 ± 0.005

Constraint on charged Higgs scenario

Model	Coefficients
2HDM (type-II) Phys. Rev. D 87, 034028	$\begin{cases} C_{S_L} = -m_b m_\tau(\mu_b)\dfrac{\tan^2\beta}{m_{H^+}^2} \\ C_{S_R} = -m_c(\mu_b)m_\tau(\mu_b)\dfrac{1}{m_{H^+}^2} \end{cases}$
General 2HDM	C_{S_L}



2HDM (type II)



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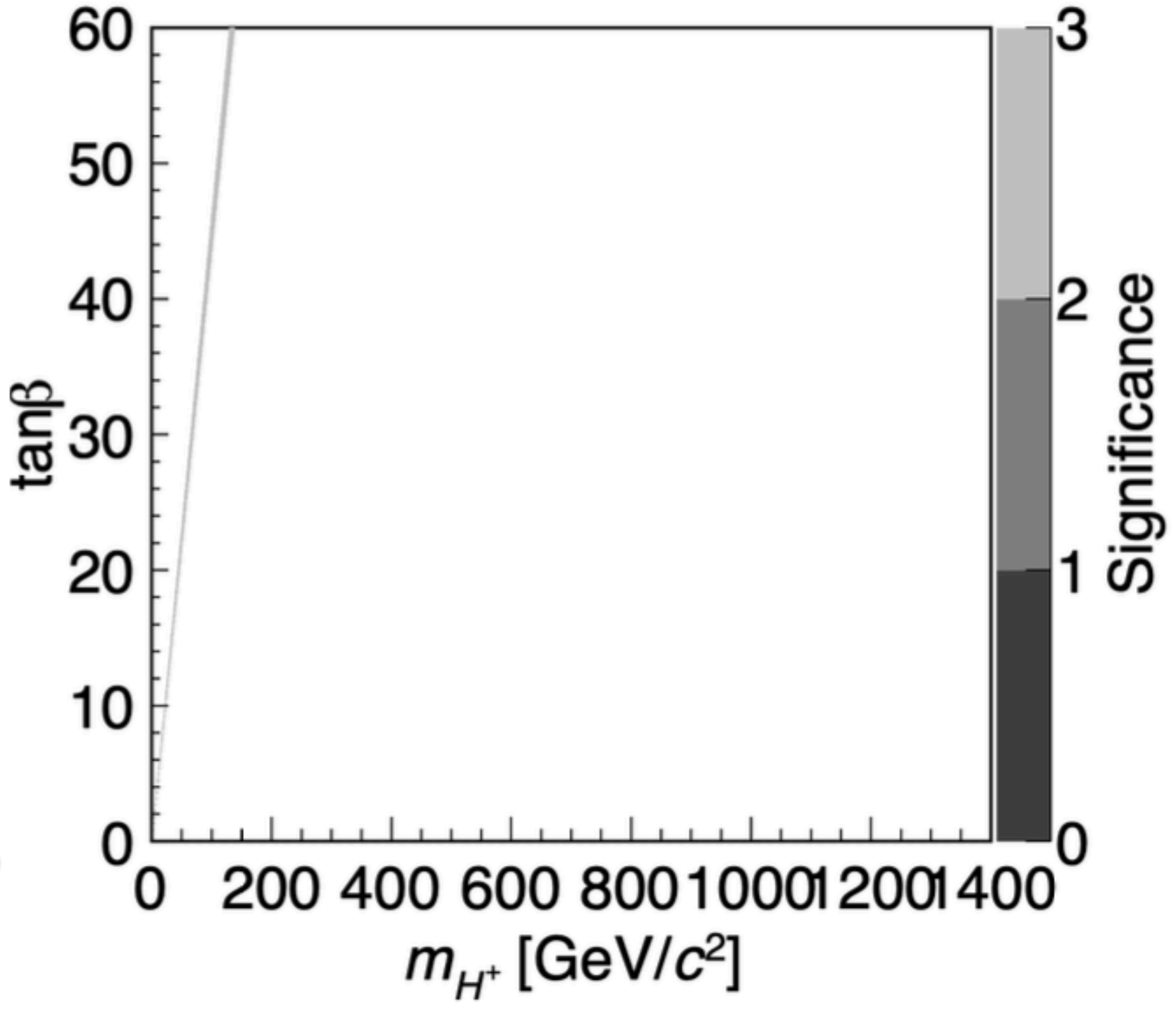
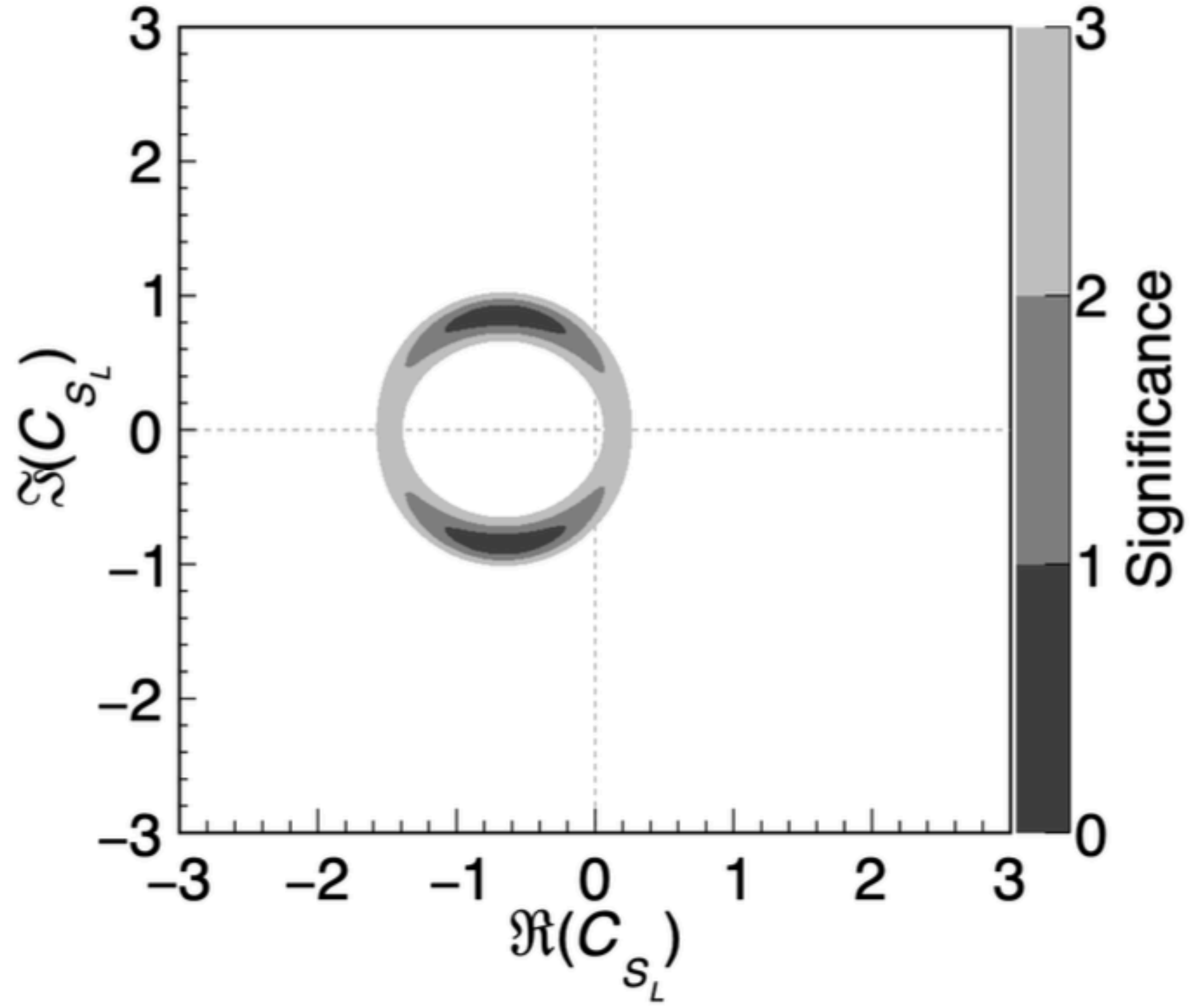


General 2HDM



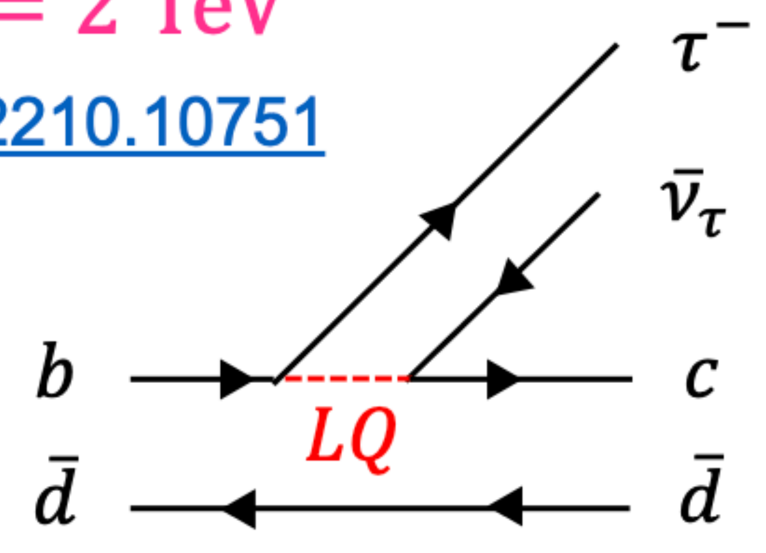
- Charged Higgs in 2HDM (type II) is disfavored
- General 2HDM still survives

Constraint on leptoquark scenario

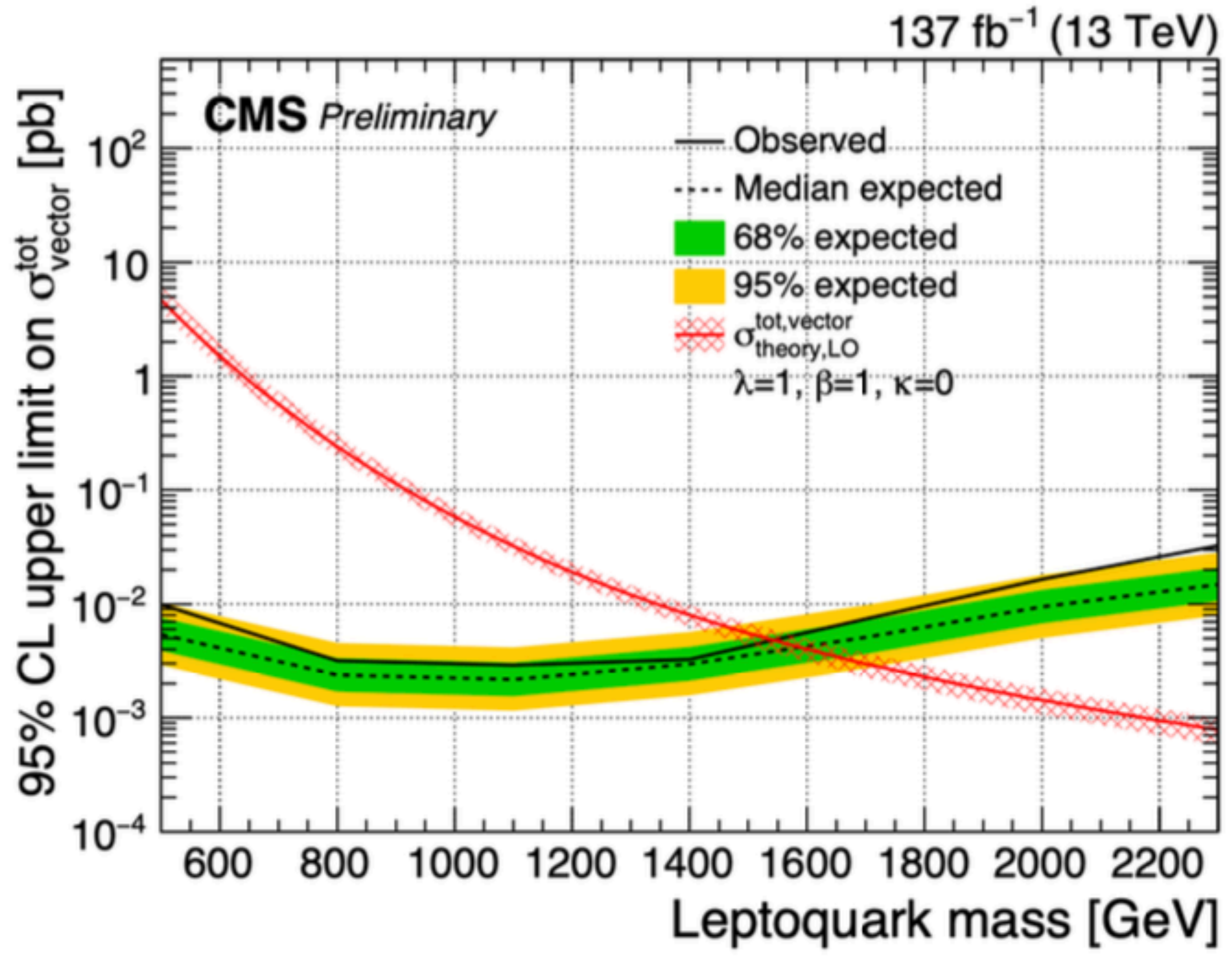
Model	Coefficients	
	$\Lambda_{LQ} = M_{LQ}$	$\mu_b = m_b$
$SU(2)_L$-singlet vector U_1^μ	C_{V_L}, C_{S_R}	C_{V_L}, C_{S_R}
$SU(2)_L$-singlet scalar S_1	C_{V_L}, $C_{S_L} = -4C_T$	C_{V_L}, $C_{S_L} = -8.7C_T$
$SU(2)_L$-doublet vector R_2	C_{V_R}, $C_{S_L} = +4C_T$	C_{V_R}, $C_{S_L} = +8.2C_T$

$M_{LQ} = 2$ TeV

arXiv:2210.10751



Vector leptoquark model



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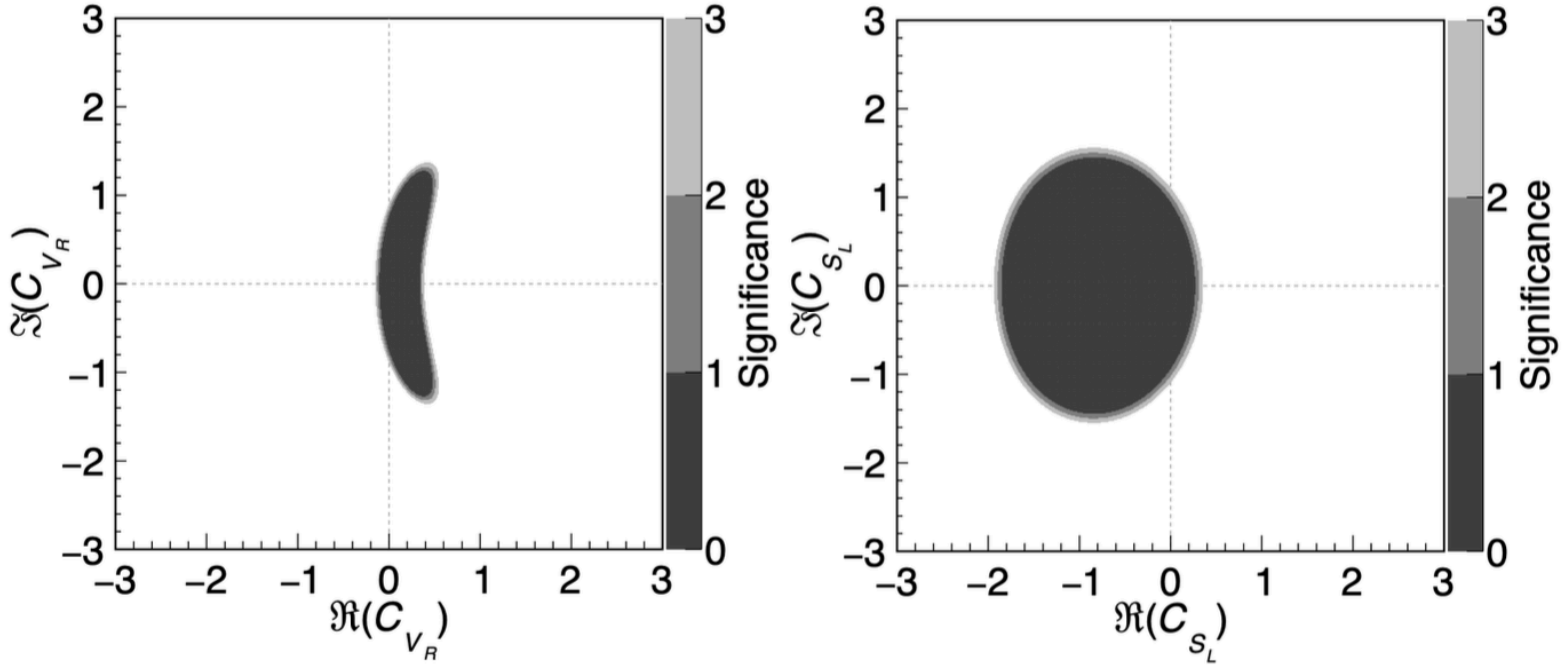
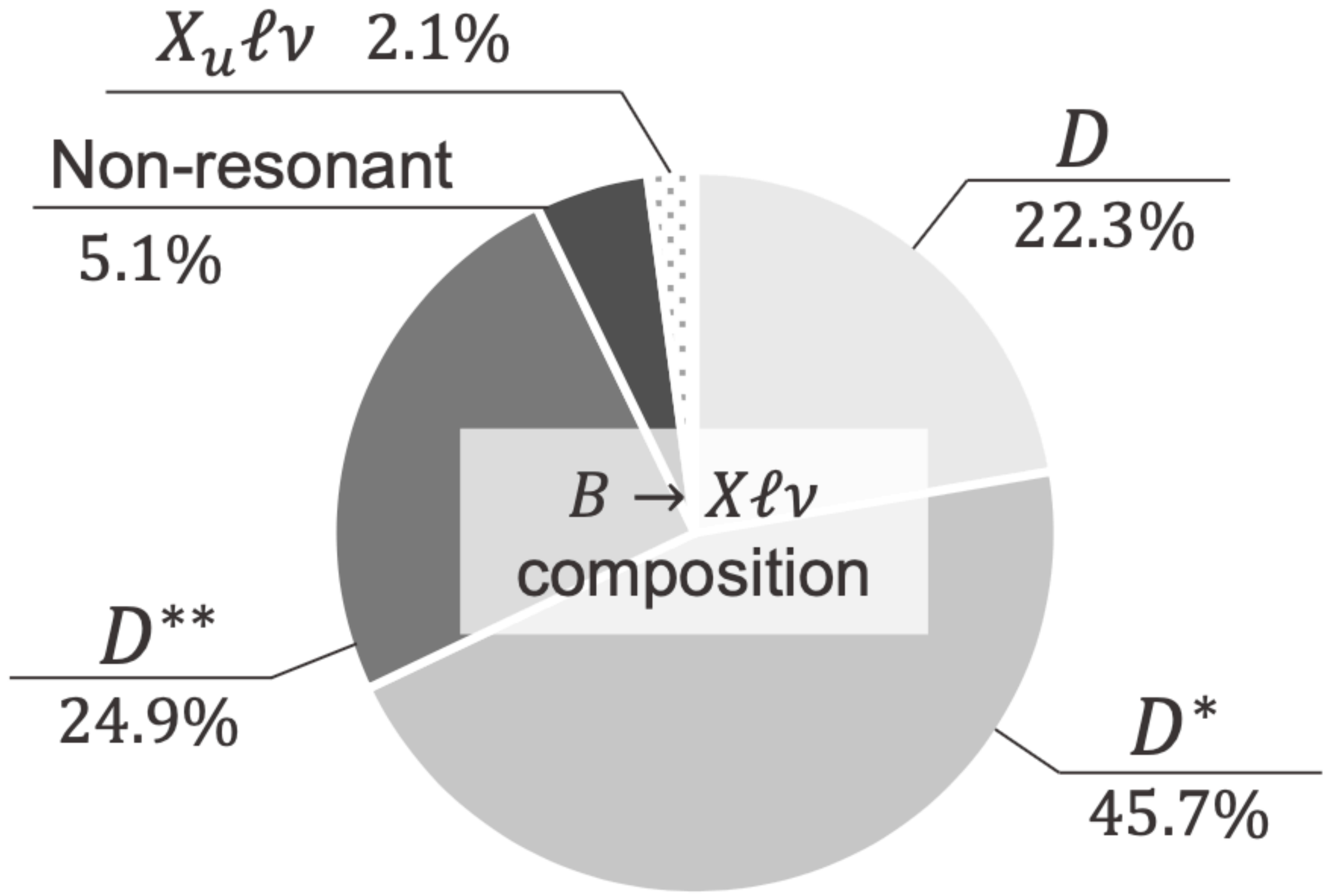
Leptoquark model (R_2 type)



- All three models have favored regions within 1σ $R(D^{(*)})$ exp. average
- $R(D^{(*)})$ can be explained with three leptoquark models of 2 TeV

LFU test by $R_{\tau/\ell}(X)$ measurement

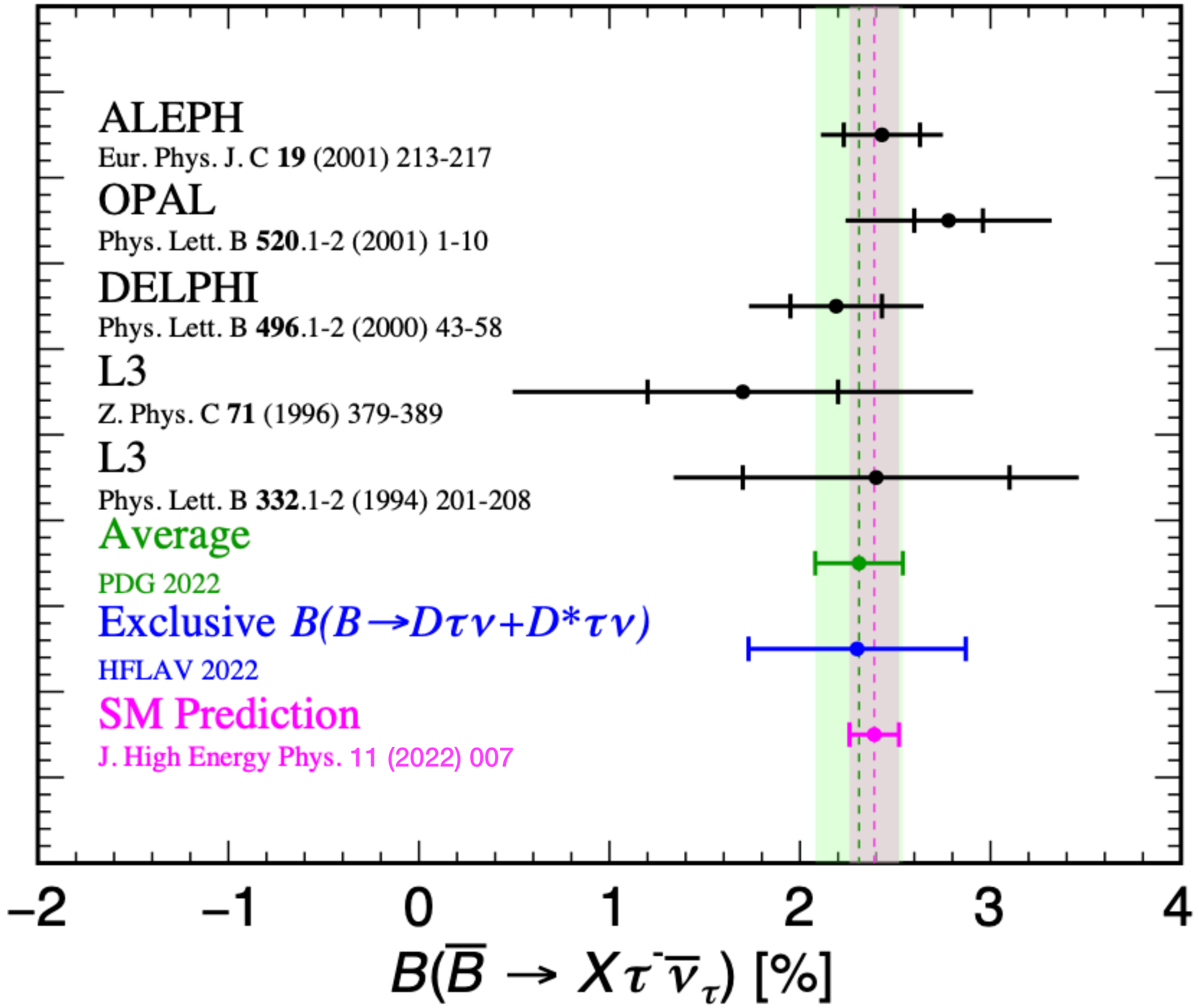
- Breakdown of $B \to Xl\nu$ branching fractions
  - ~ 2/3 overlap with D and D^*
    - ~ 3/4 D decay to ν, K_L^0, $n\pi$ …
  - ~ 1/3 contribution from D^{**} and nonresonant X_c
- Multiple LEP experiments measured Br($B \to X\tau\nu$)
  - Br($B \to X\tau\nu$) are completely saturated by D/D^* BFs
  - ➡ An update measurement is needed



- $R(X)$ is critical cross-check of $R(D^{(*)})$, largest contribution from $R(D^{(*)})$, a partially complementary test of LFU

$$R(X_{\tau/\ell}) = \frac{Br(\bar{B} \to X\tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to X\ell^- \bar{\nu}_\ell)}$$

- $R(X)$ has never been measured



Results of $R_{\tau/\ell}(X)$ for LFU test

- Main systematics
  - Adjustment to MC (form factor, D and B branching factions)
  - Sample size in sideband for reweighting

- First Belle II preliminary $R_{\tau/\ell}(X)$ result

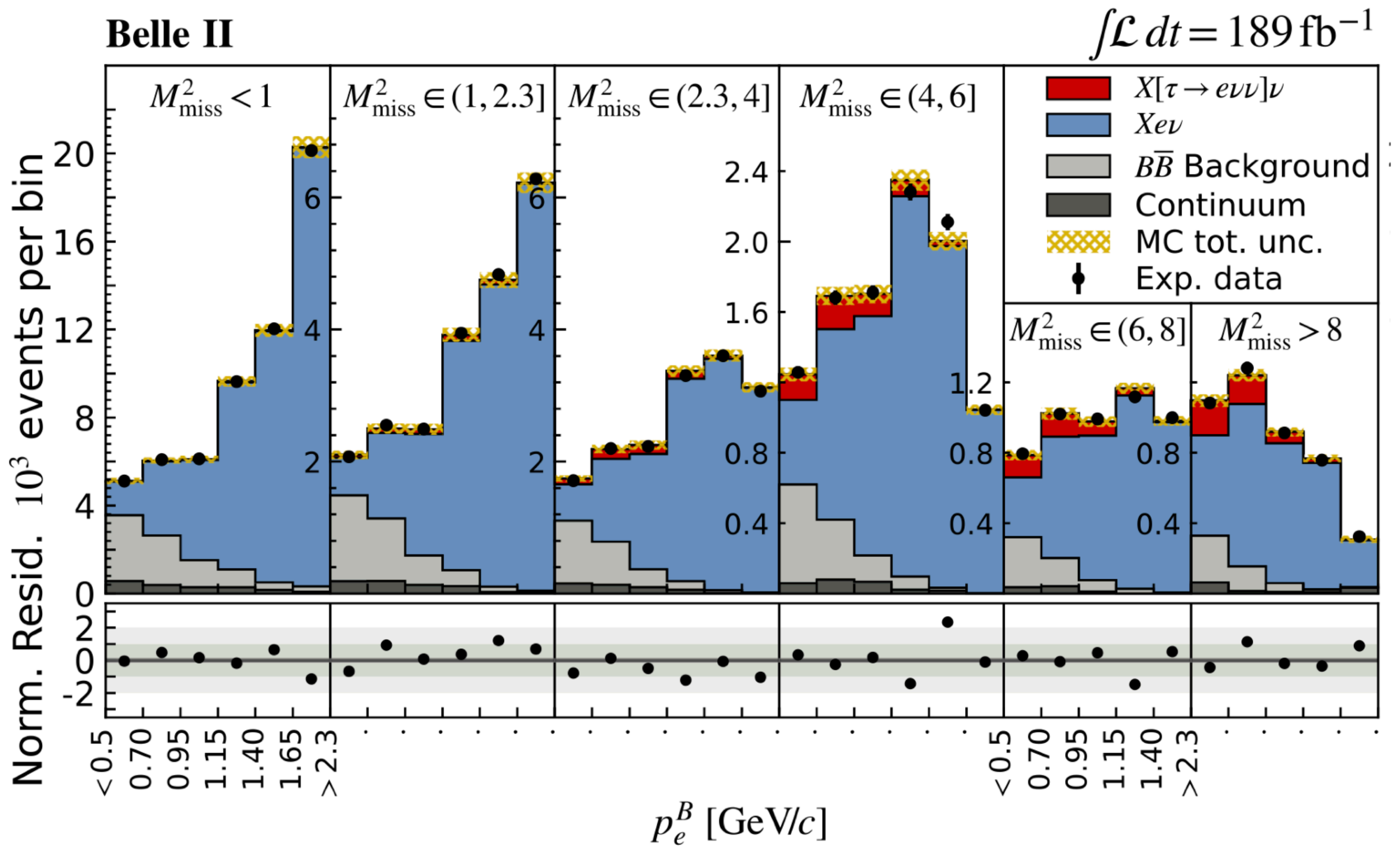
  $R_{\tau/\ell}(X) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$

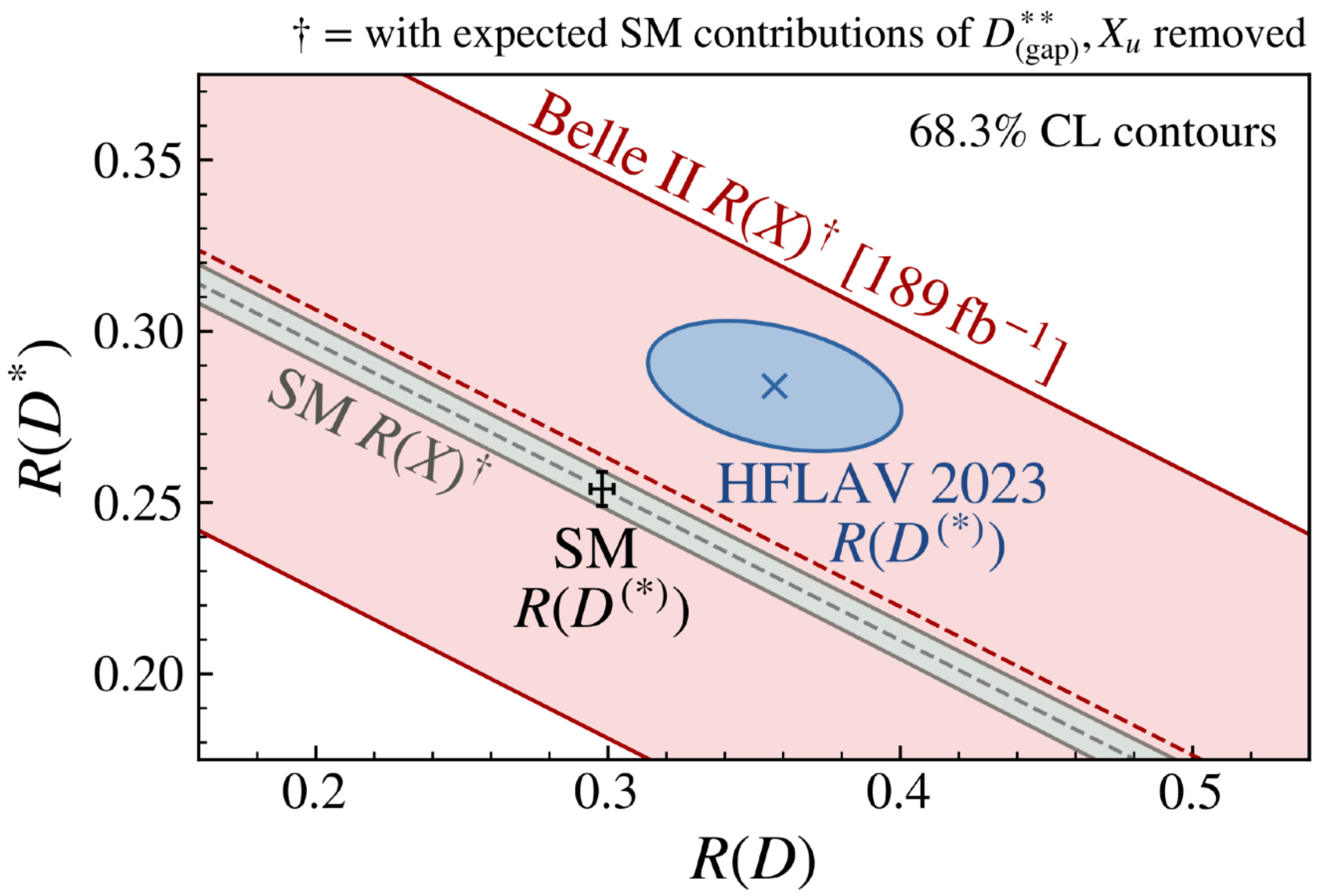
  $R_{\tau/e}(X) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$

  $R_{\tau/\mu}(X) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$

- Consistent with rough SM expectation

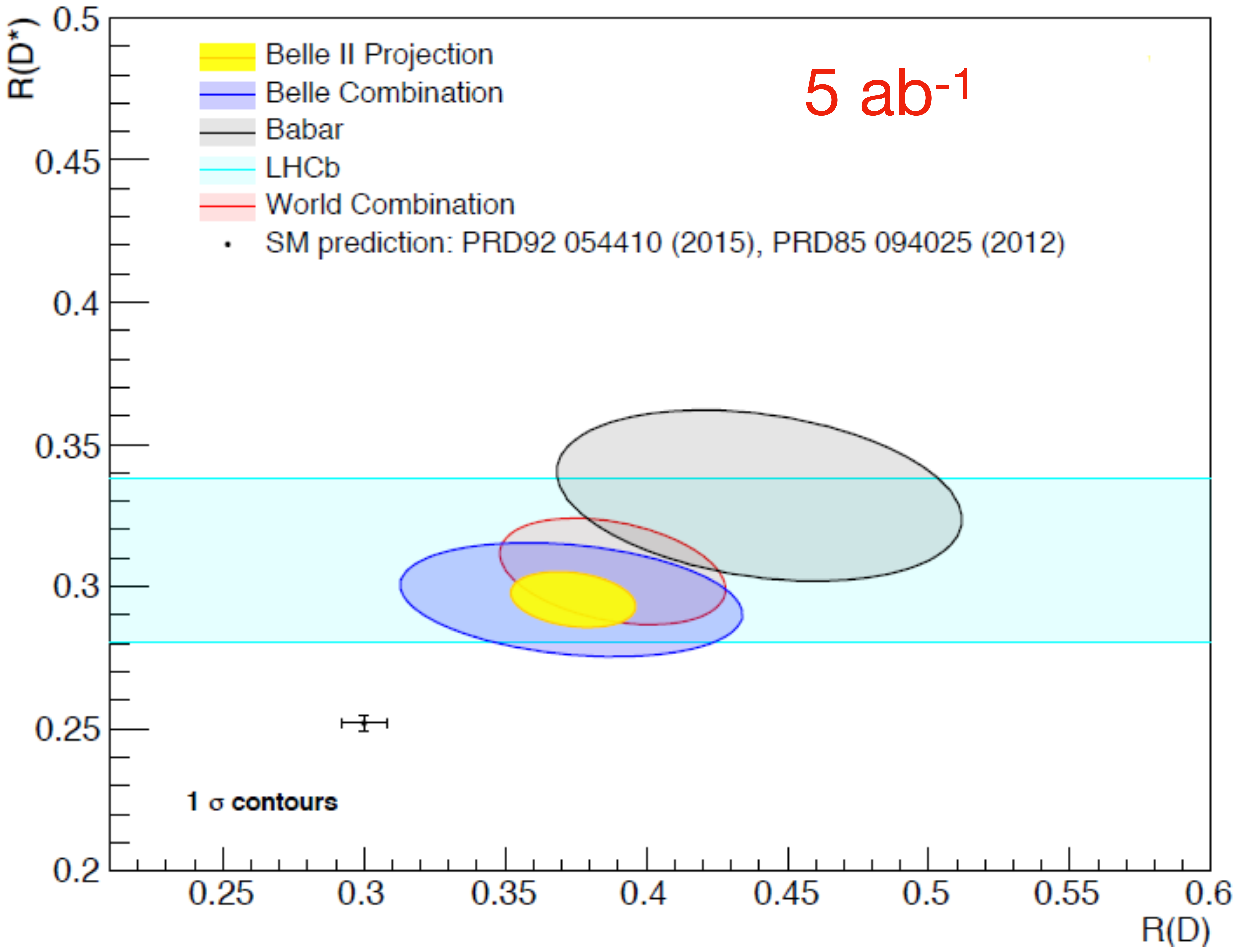
  $R_{\tau/l}(X)_{SM} \approx 0.222$



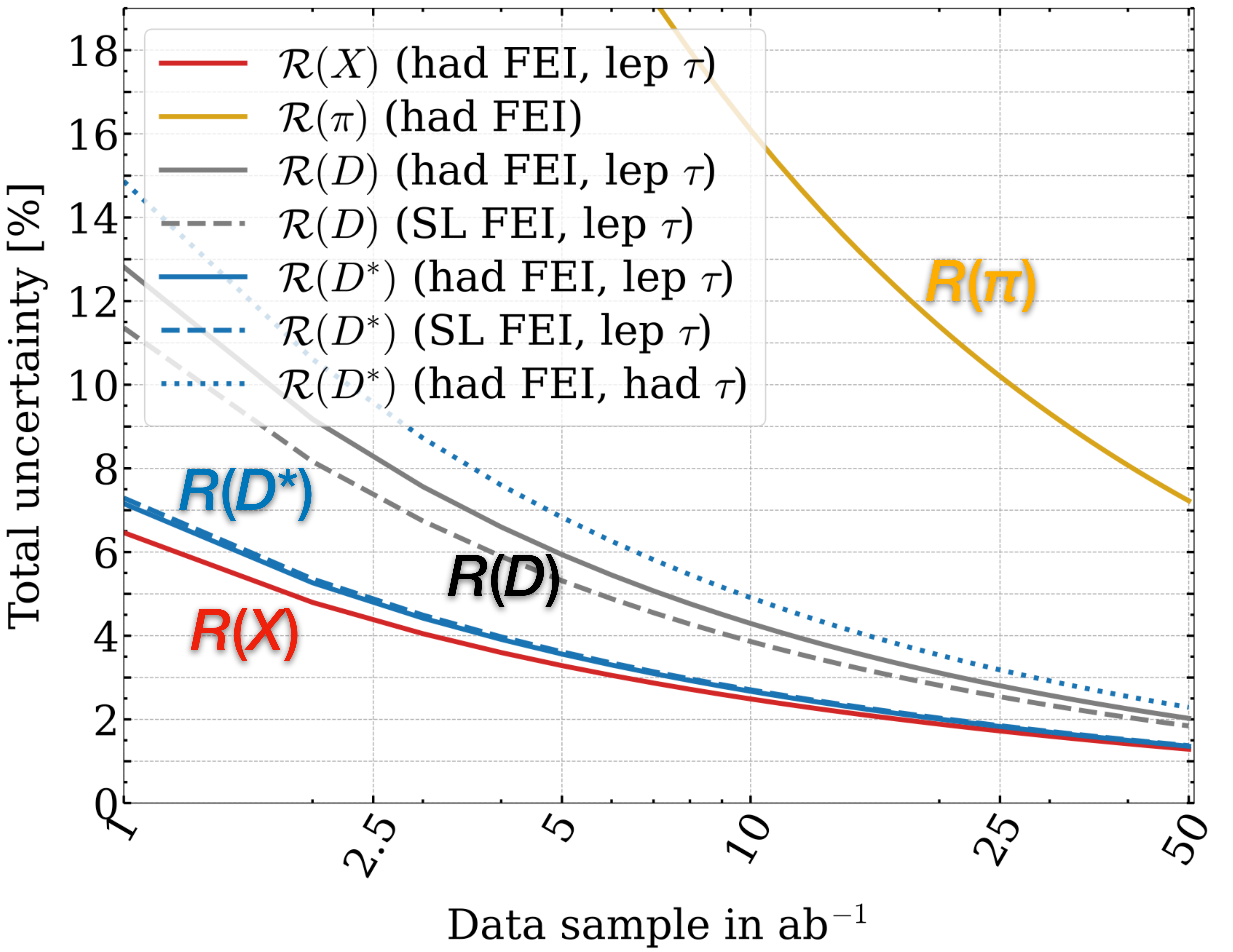


Expected sensitivity of LFU test at Belle II

The Belle II Physics Book, PTEP 2019, 123C01



arXiv:2207.06307



Summary and prospects

- $R(D^{(*)})$ shows 3.3σ deviation between experimental average value and standard model prediction
  - Hint of Lepton Flavor Universality Violation

- Belle II performed new tests of LFU based on 189 fb^{-1} data

$$R_{\tau/\ell}(D^*) = 0.267\ ^{+0.041}_{-0.039}\ \text{(stat)}\ ^{+0.028}_{-0.033}\ \text{(syst)}$$

$$R_{\tau/\ell}(X) = 0.228 \pm 0.016\ \text{(stat)} \pm 0.036\ \text{(syst)}$$

- SuperKEKB/Belle II resumed operation at the beginning of 2024 after LS1