Soft QCD: Theory

Peter Skands (CERN Theoretical Physics Dept)

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Questions

Pileup

- How much? In central & fwd acceptance?
- Structure: averages + fluctuations, particle composition, lumpiness, …
- Scaling to 13 TeV and beyond

Underlying Event ~ "A handful of pileup" ?

- Hadronizes with Main Event → "Color reconnections"
- Additional "minijets" from multiple parton interactions

Hadronization

- Models from the 80ies, mainly constrained in 90ies
- Meanwhile, perturbative models have evolved
  - Dipole/Antenna showers, ME matching, NLO corrections, …
  - Precision → re-examine non-perturbative models and constraints
  - New clean constraints from LHC (& future colliders)?
- Hadronization models ⇄ analytical NP corrections?

Uses and Limits of "Tuning"

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Uses and Limits of "Tuning"

From Hard to Soft

Factorization and IR safety

Main tools for jet calculations

Corrections suppressed by powers of Λ_{QCD}/Q_{Hard}

Soft QCD / Pileup

NO HARD SCALE

Typical Q scales ~ Λ_{QCD}

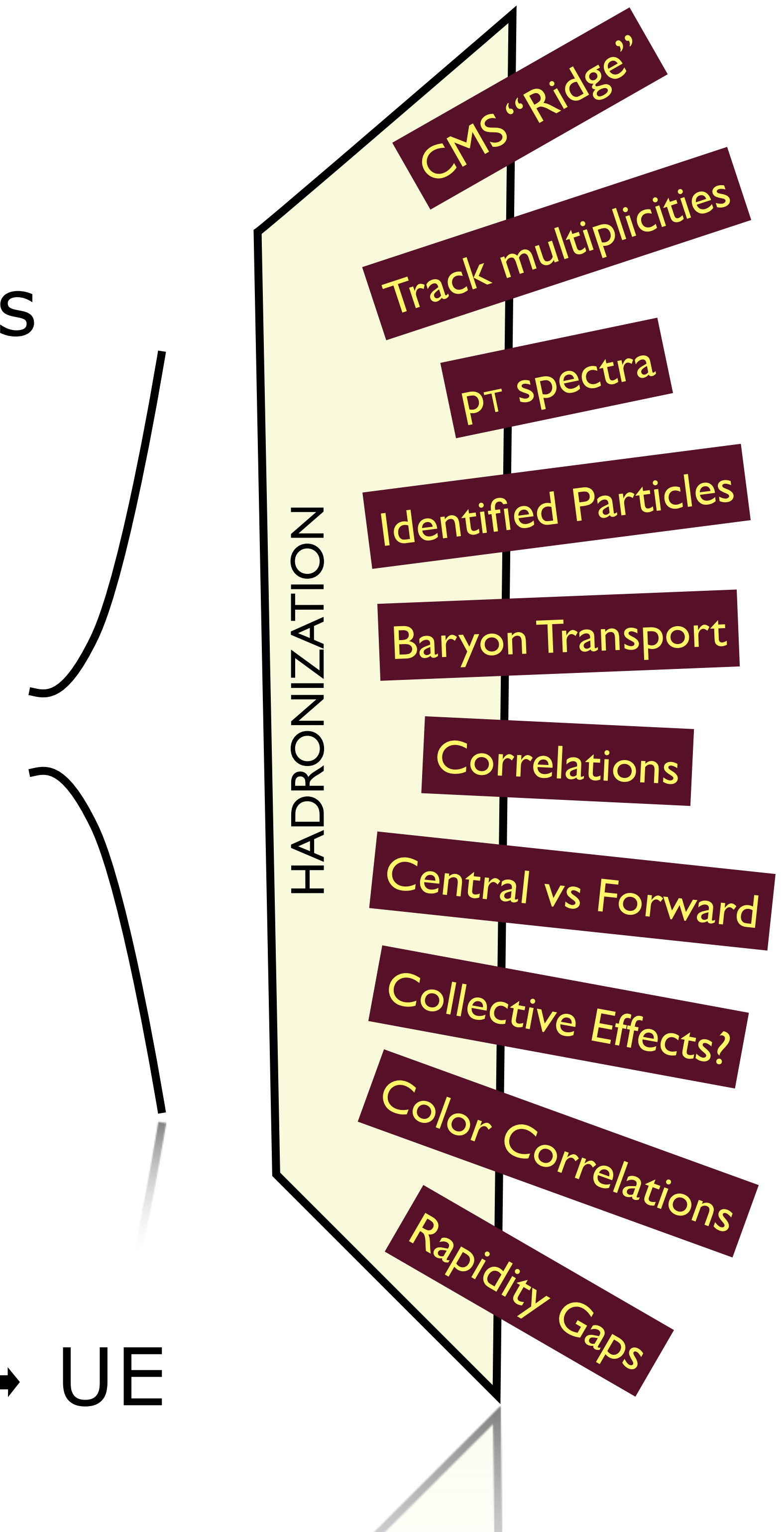
Extremely sensitive to IR effects

→ Excellent LAB for studying IR effects

~ ∞ statistics for min-bias

→ Access tails, limits

Universality: Recycling PU ↔ MB ↔ UE

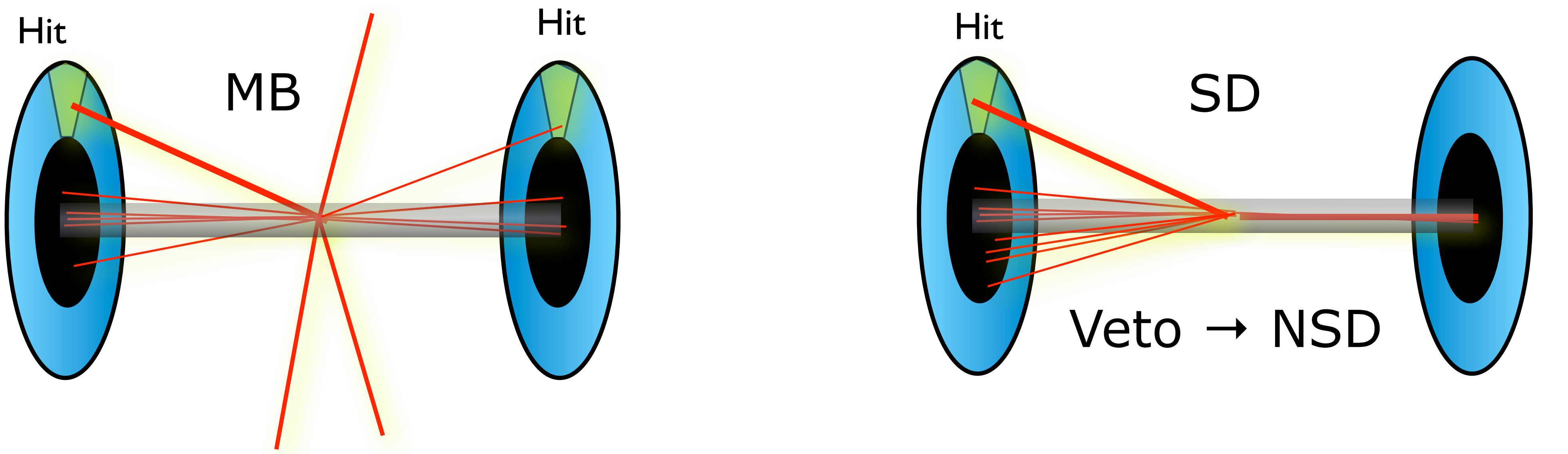


What is Pileup / Min-Bias?

We use Minimum-Bias (MB) data to test soft-QCD models

Pileup = "Zero-bias"

"Minimum-Bias" typically suppresses diffraction by requiring two-armed coincidence, and/or ≥ n particle(s) in central region



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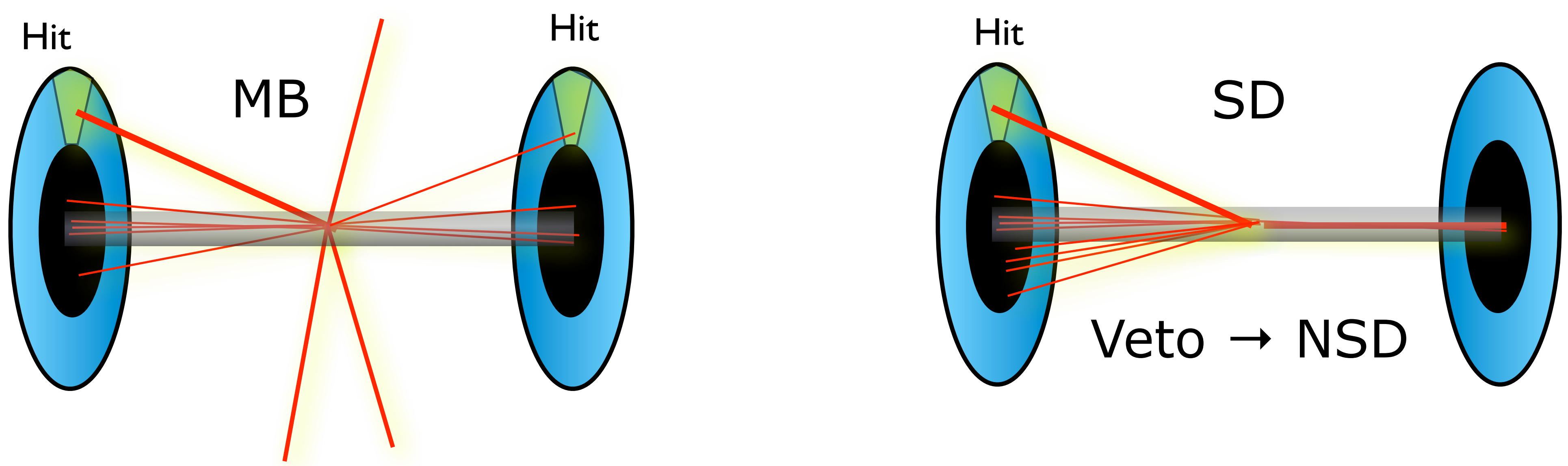


→ Pileup contains more diffraction than Min-Bias

Total diffractive cross section ~ 1/3 σ_{inel}

Most diffraction is low-mass → no contribution in central regions

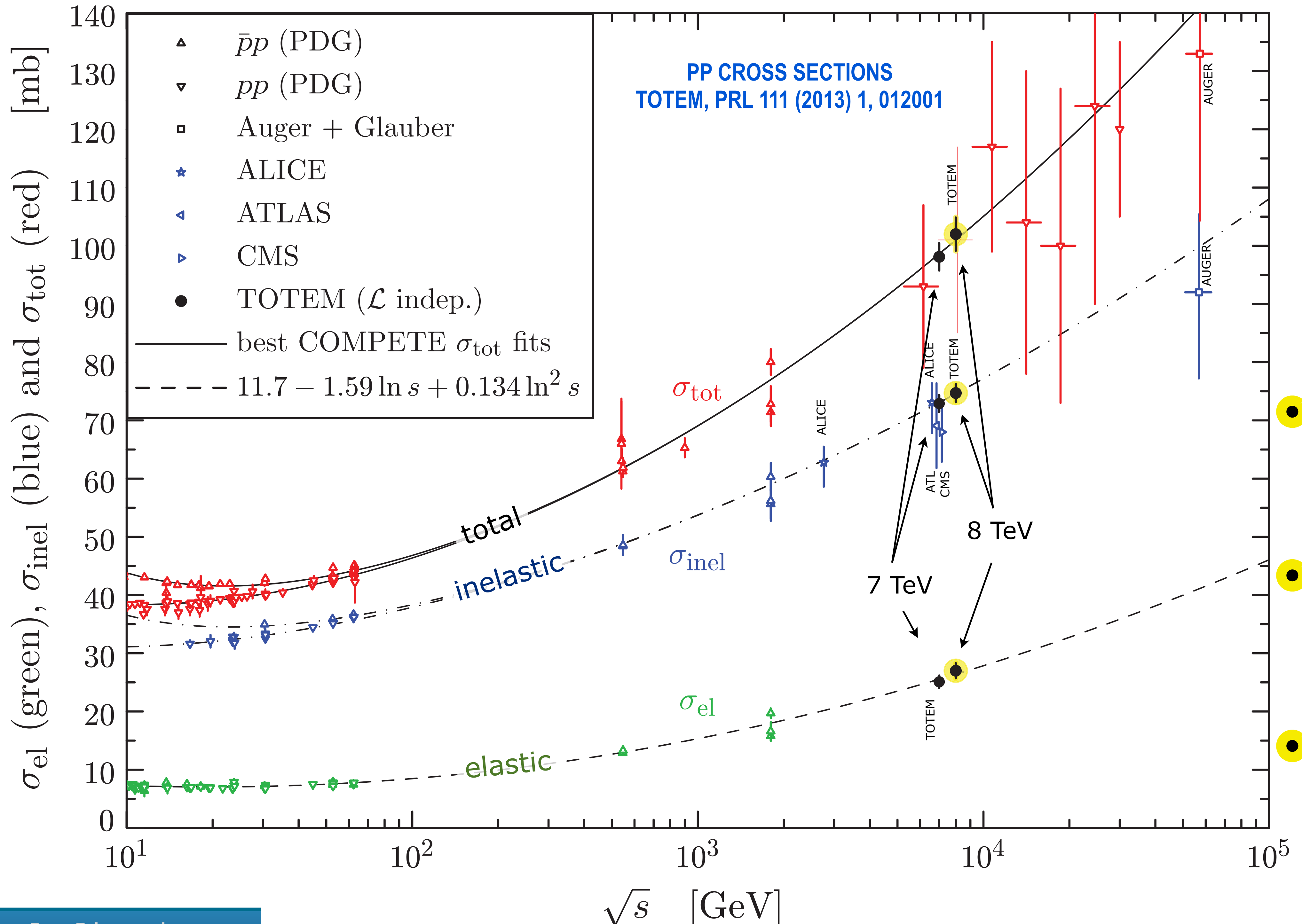
High-mass tails could be relevant in FWD region

→ direct constraints on diffractive components (→ later)

The Total Cross Section

$$\text{Pileup rate} \propto \sigma_{\text{tot}}(s) = \sigma_{\text{el}}(s) + \sigma_{\text{inel}}(s) \propto s^{0.08} \text{ or } \ln^2(s)\ ?$$

Donnachie-Landshoff Froissart-Martin Bound



(2.9%) $\sigma_{\text{tot}}(8\text{ TeV}) = 101 \pm 2.9$ mb

(2.3%) $\sigma_{\text{inel}}(8\text{ TeV}) = 74.7 \pm 1.7$ mb

(5.1%) $\sigma_{\text{el}}(8\text{ TeV}) = 27.1 \pm 1.4$ mb

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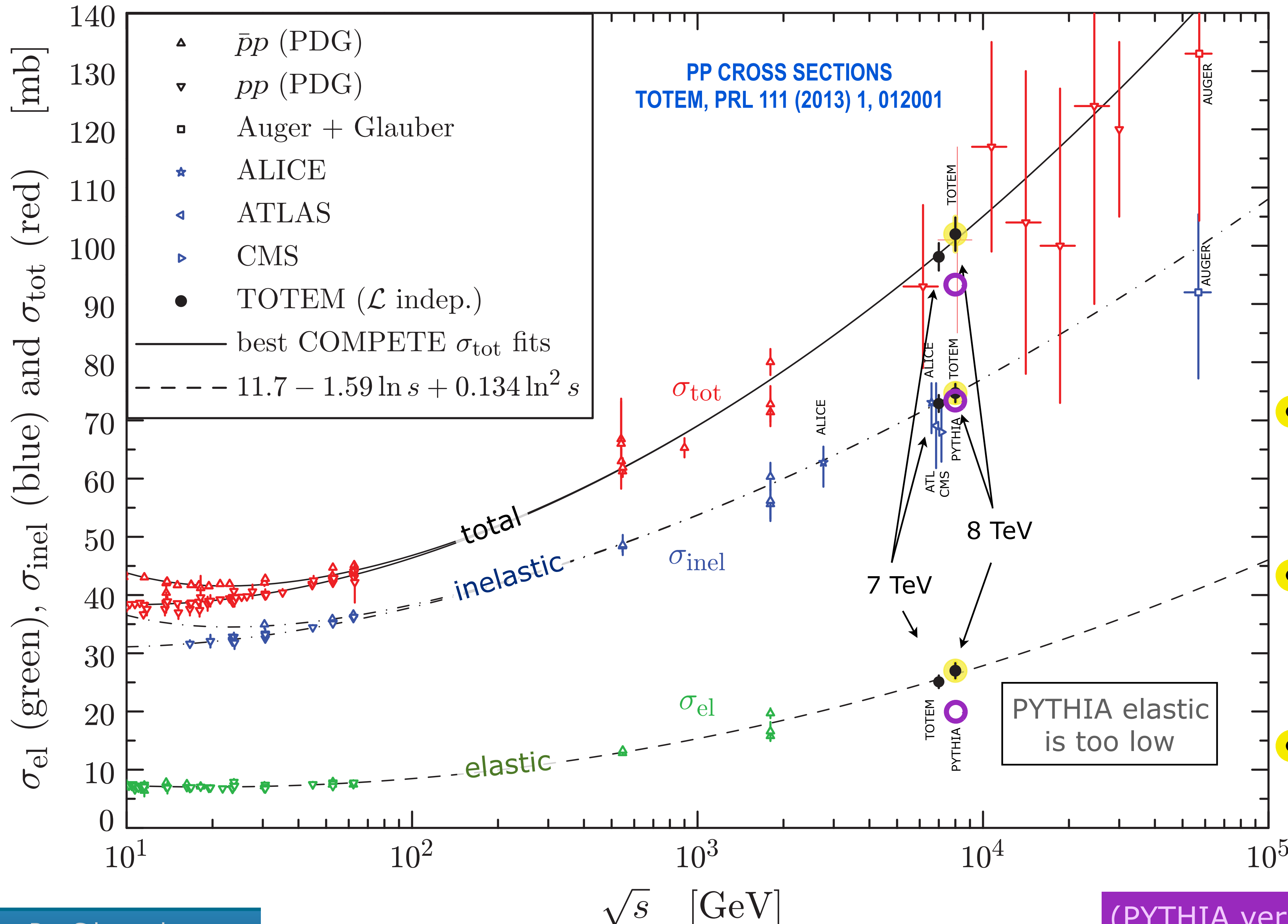

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PYTHIA: 93 mb

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(PYTHIA versions: 6.4.28 & 8.1.80)

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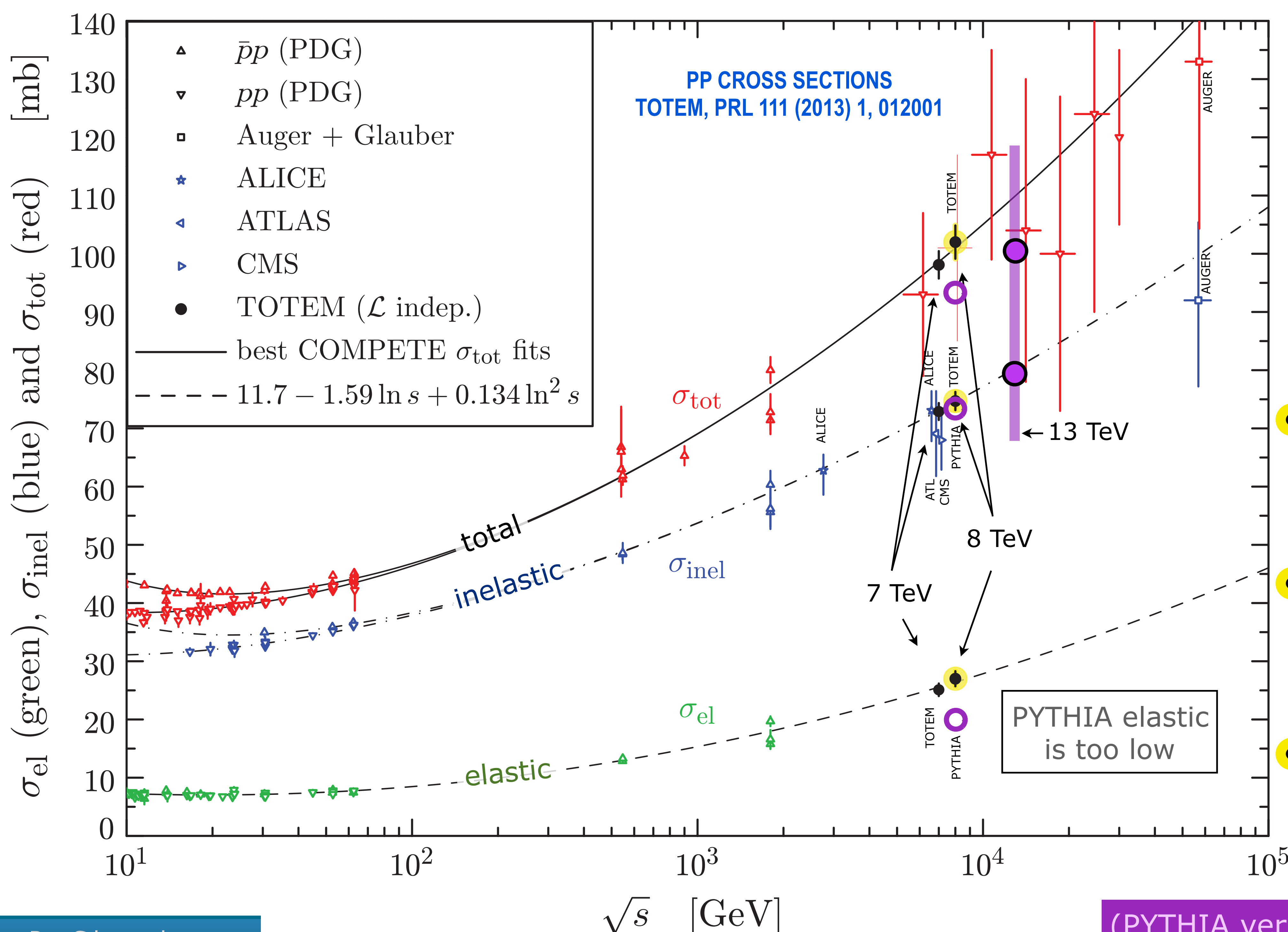

$\sigma_{\rm tot}(13\text{ TeV}) \sim 110 \pm 6$ mb

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$\sigma_{\rm inel}(13\text{ TeV}) \sim 80 \pm 3.5$ mb

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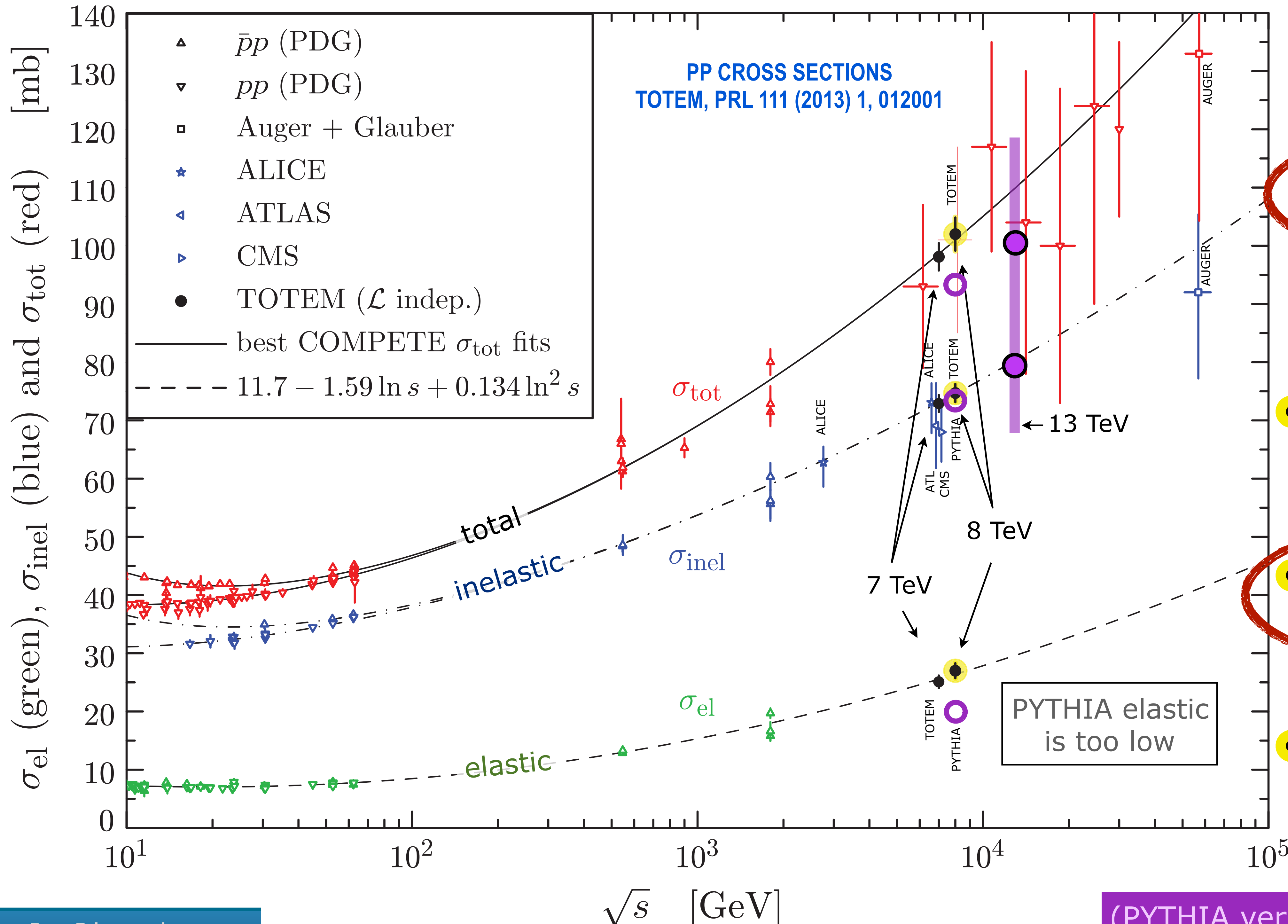

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The Inelastic Cross Section

First try: decompose $\sigma_{\mathrm{inel}} = \sigma_{\mathrm{sd}} + \sigma_{\mathrm{dd}} + \sigma_{\mathrm{cd}} + \sigma_{\mathrm{nd}}$

+ Parametrizations of diffractive components: dM^2/M^2

PYTHIA:

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\,,$$

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+ Integrate and solve for σ_{nd}

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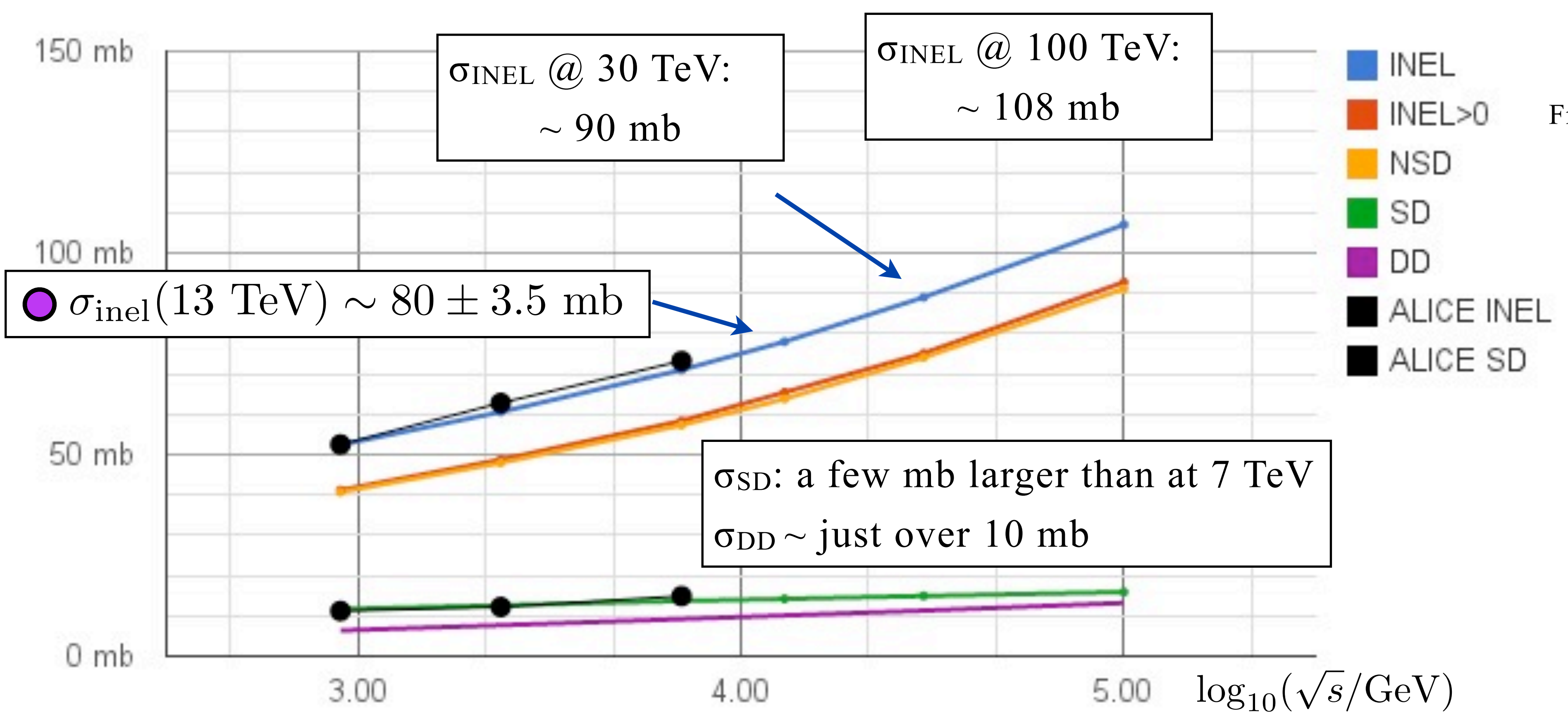

What Cross Section?

INEL	Total Inelastic
INEL>0	Fraction with one charged particle in |η|<1
NSD	Ambiguous Theory Definition
SD	Ambiguous Theory Definition
DD	Ambiguous Theory Definition
ALICE INEL	Observed fraction corrected to total
ALICE SD	ALICE def : SD has MX<200

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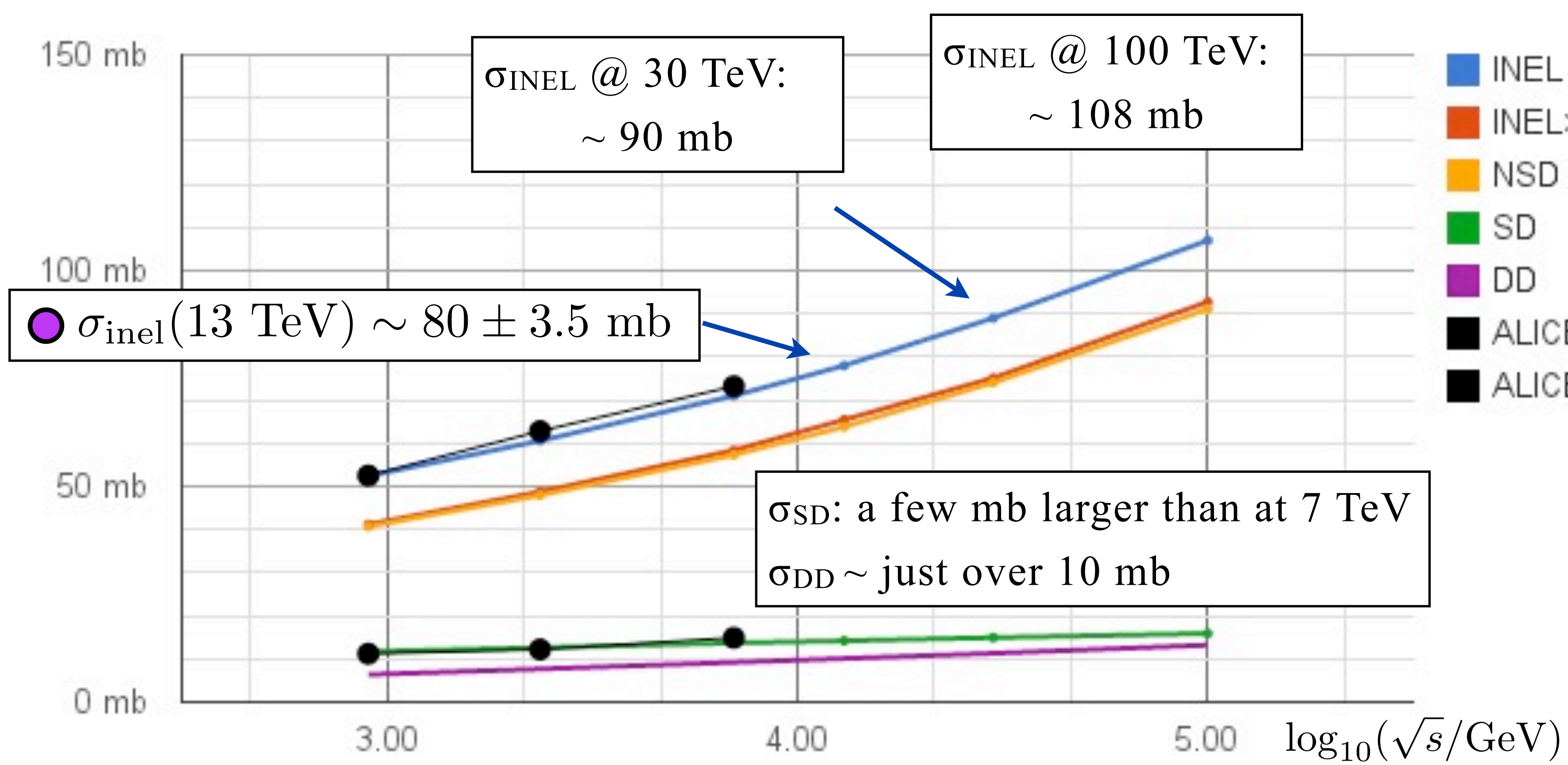

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Note problem of principle: Q.M. requires **distinguishable final states**

Models of Soft QCD - Disclaimer

May not always reflect "best" TH understanding

Not just a matter of cranking perturbative orders

Harder due to requirement of fully differential **dynamical modeling** (event generators), not just cross section formulae

May not always reflect "best" EXP constraints

Not just a matter of "tuning"

(+ *tunnel vision:* exp comparisons for searches or EW measurements rarely formulated as QCD constraints)

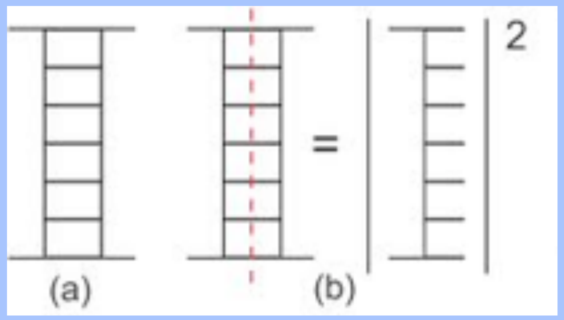
Modeling: identify "new" physics + build and constrain models (beyond perturbative leading-twist)

Few people working on soft QCD models → long cycles

Dynamical Models of Soft QCD

See e.g. Reviews by MCnet [arXiv:1101.2599] and KMR [arXiv:1102.2844]

A — Regge Theory



Optical Theorem

+ Eikonal multi-Pomeron exchanges

$\sigma_{tot,inel} \propto \log^2(s)$

Froissart-Martin Bound

Cut Pomerons → Flux Tubes (strings)

Uncut Pomerons → Elastic (& eikonalization)

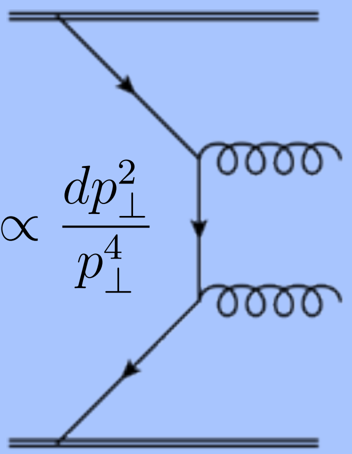
Cuts unify treatment of all soft processes

EL, SD, DD, … , ND

(Perturbative contributions added above Q_0)

B — Parton Based

$$d\sigma_{2\to 2} \propto \frac{dp_\perp^2}{p_\perp^4} \otimes \text{PDFs}$$



+ Unitarity & Saturation

→ Multi-parton interactions (MPI)

+ Parton Showers & Hadronization

Regulate dσ at low p_{T0} ~ few GeV

Screening/Saturation → energy-dependent p_{T0}

Total cross sections from Regge Theory

(e.g., Donnachie-Landshoff + Parametrizations)

+ "Mixed"

E.g., QGSJET, SIBYLL

E.g., PHOJET, EPOS, SHERPA-KMR

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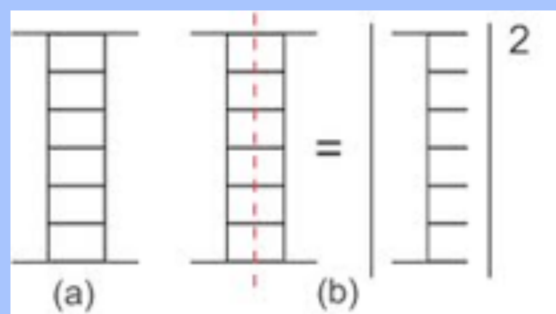

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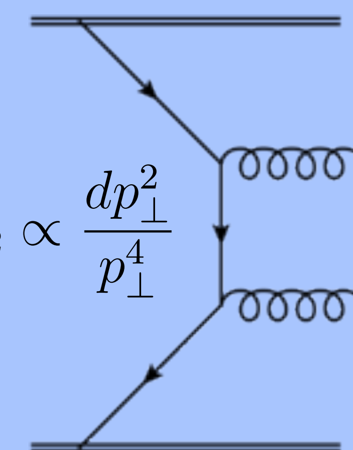

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Parton-Based Models

Main applications: Central Jets/EWK/top/ Higgs/New Physics

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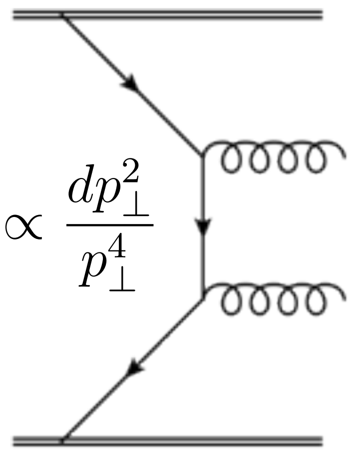

High Q^2 and finite x

See also Connecting hard to soft: KMR, EPJ C71 (2011) 1617 + PYTHIA "Perugia Tunes": PS, PRD82 (2010) 074018 + arXiv:1308.2813

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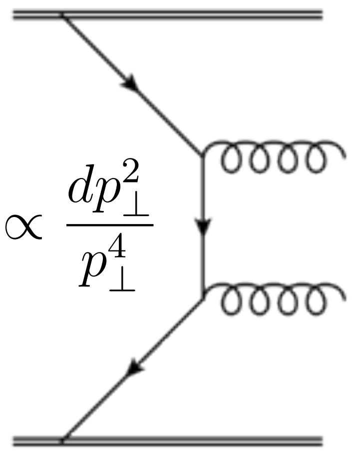

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High Q^2 and finite x

Extrapolation to soft scales delicate.
Impressive successes with MPI-based models but still far from a solved problem

- Form of PDFs at small x and Q^2
- Form and E_{cm} dependence of p_{T0} regulator
- Modeling of the diffractive component
- Proton transverse mass distribution
- Colour Reconnections, Collective Effects

Saturation

See talk on UE by W. Waalewijn

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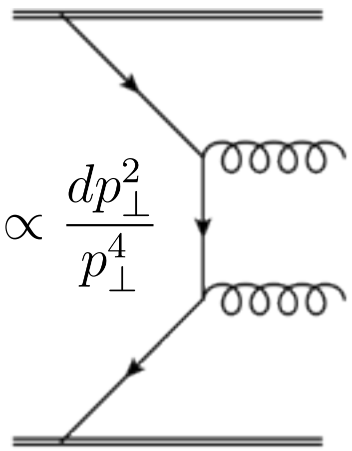

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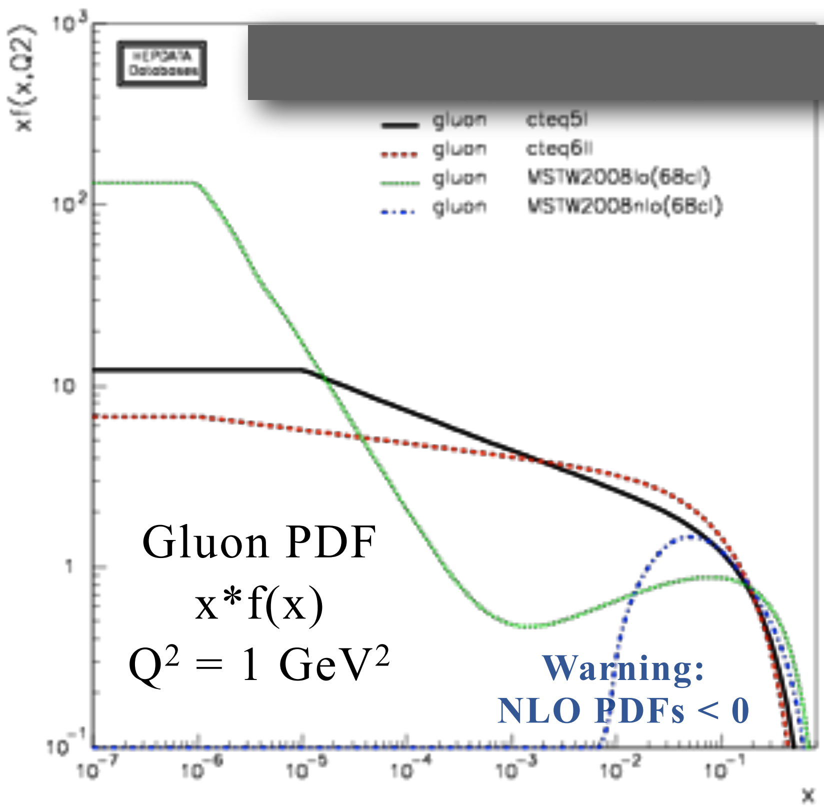
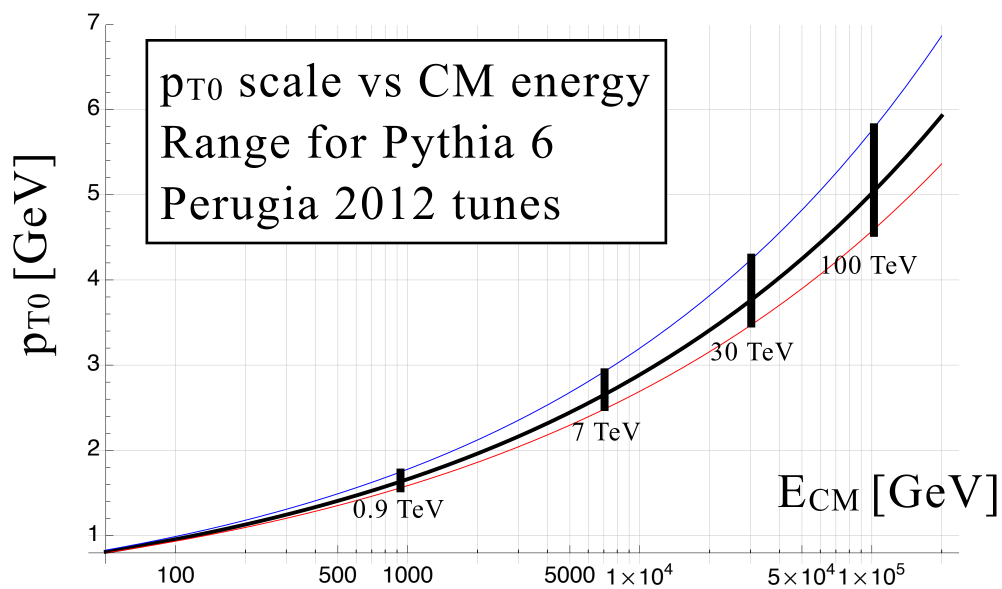
Poor Man's Saturation





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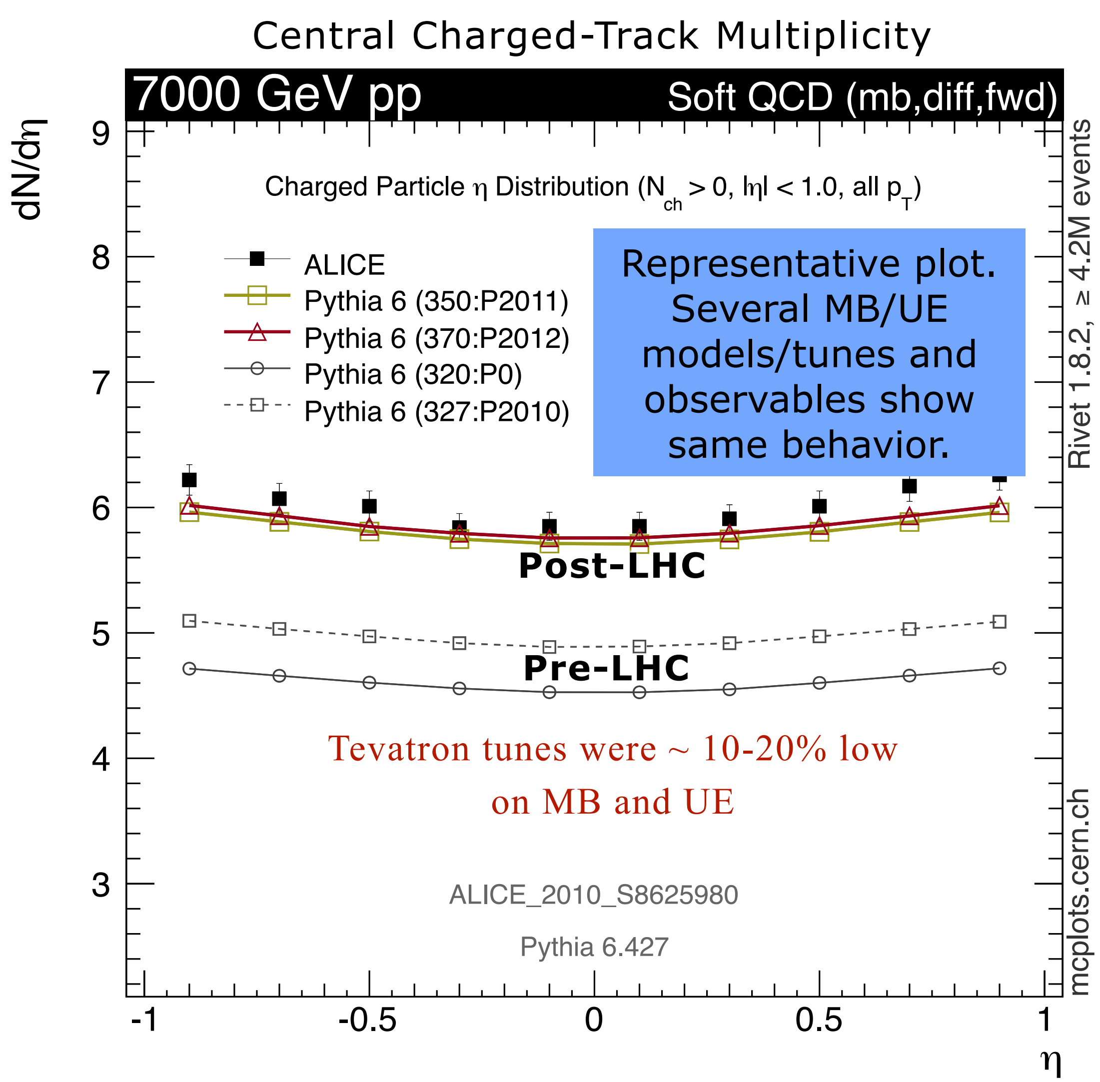
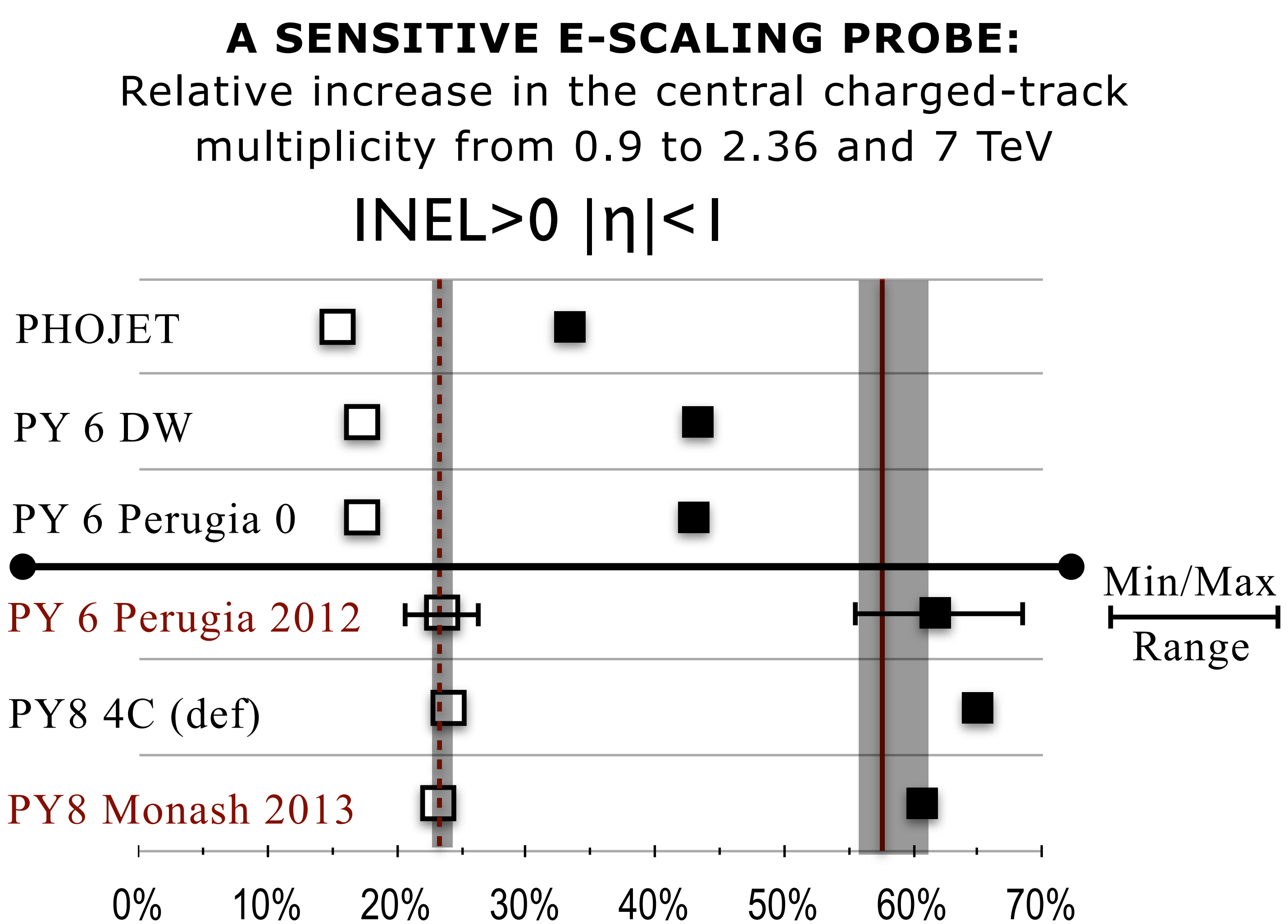
Minimum-Bias: Averages

Discovery at LHC
Min-Bias & UE are 10-20% larger than we thought
Scale a bit faster with energy
→ Be sure to use up-to-date (LHC) tunes

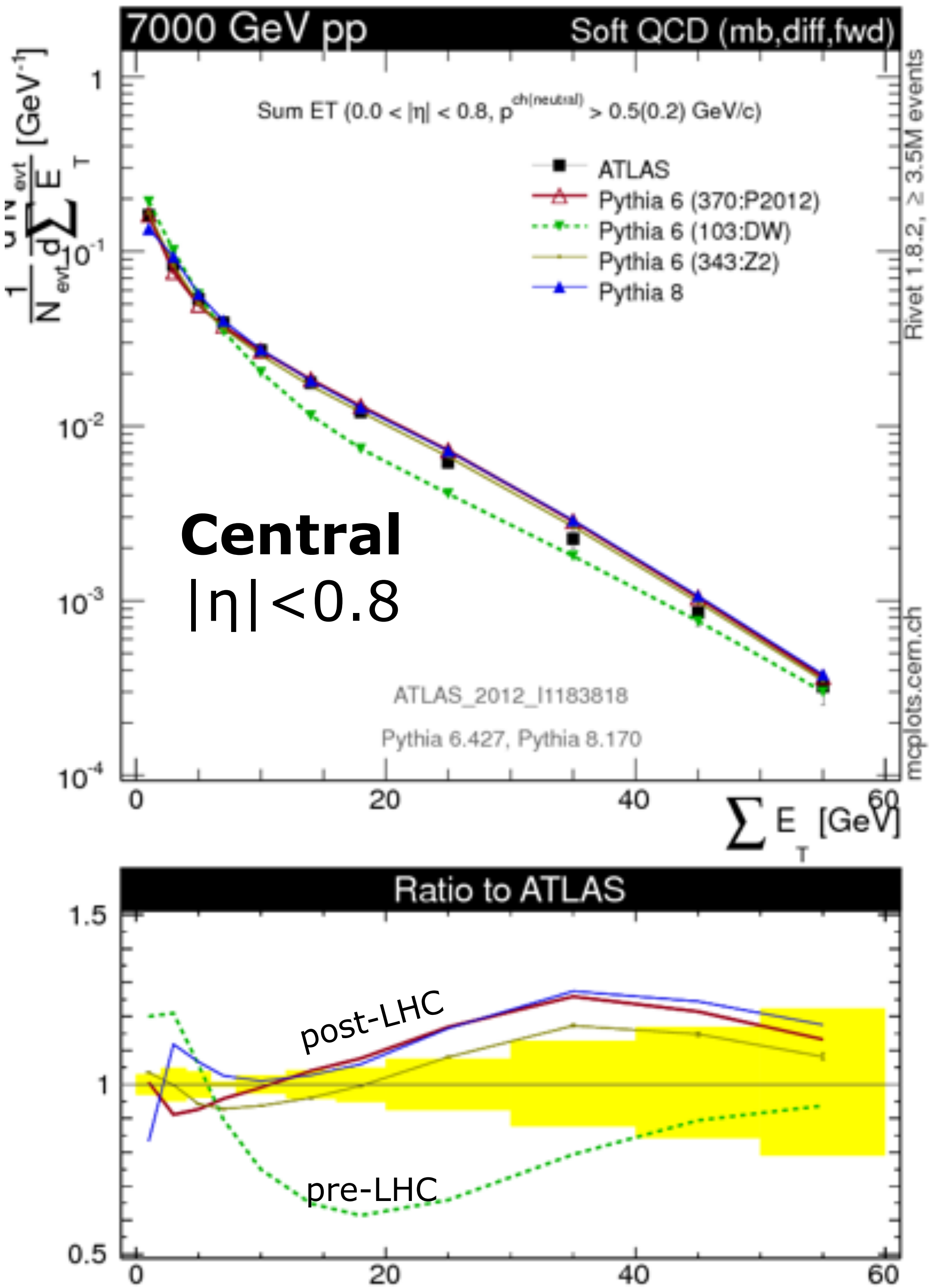


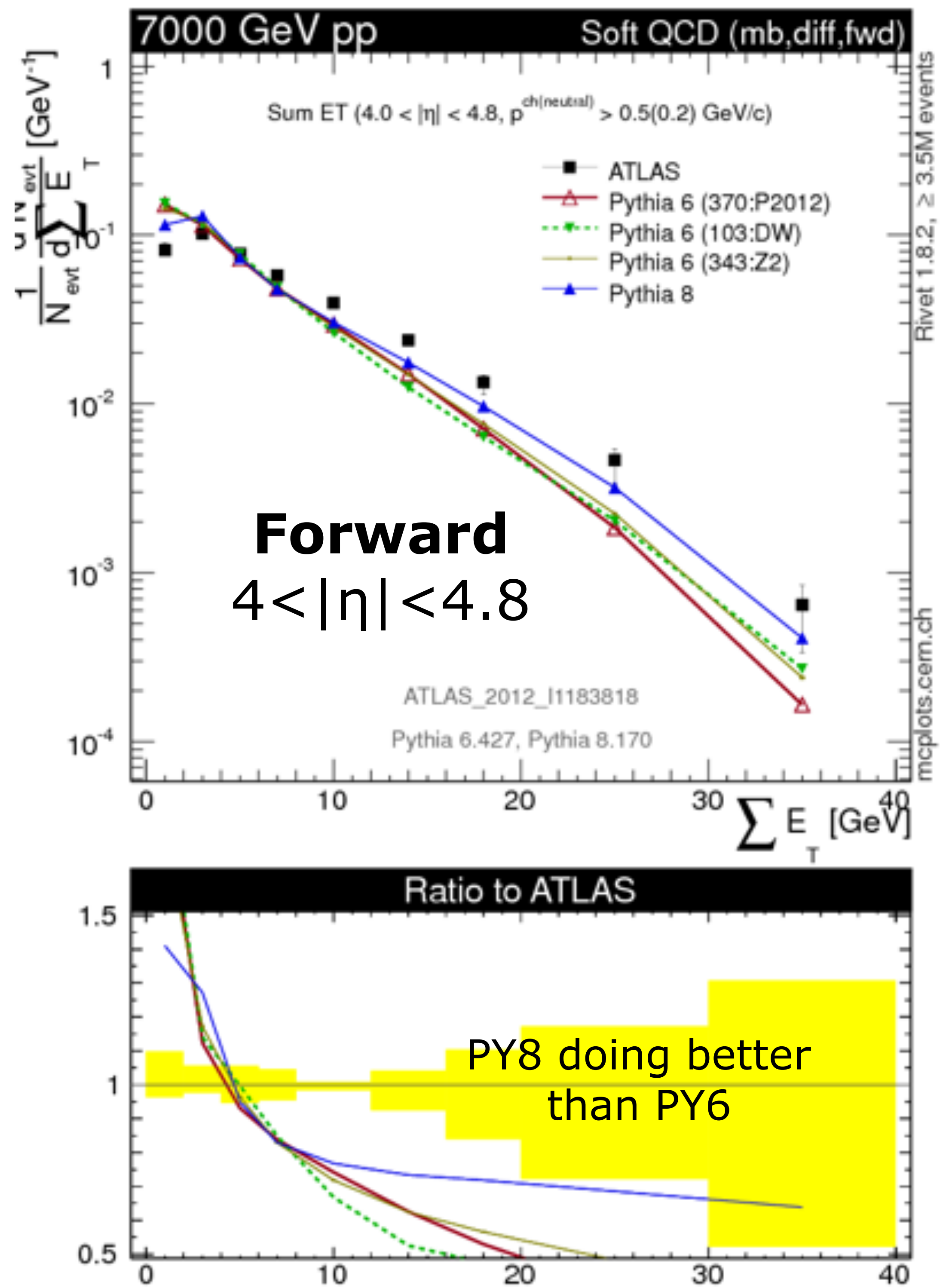


Data from ALICE EPJ C68 (2010) 345, Plot from arXiv:1308.2813

See also energy-scaling tuning study, Schulz & PS, EPJ C71 (2011) 1644

Sum(E_T)

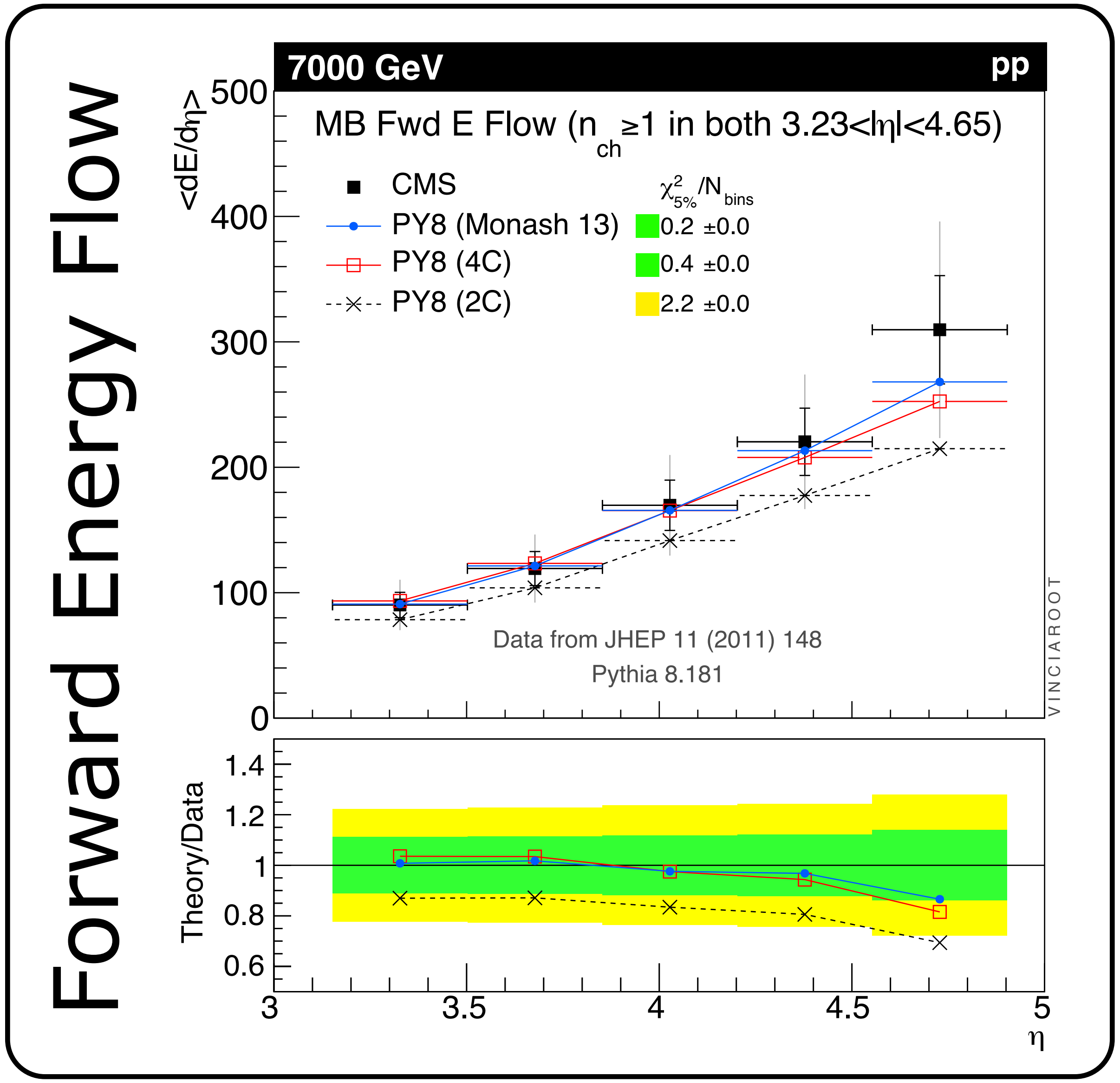


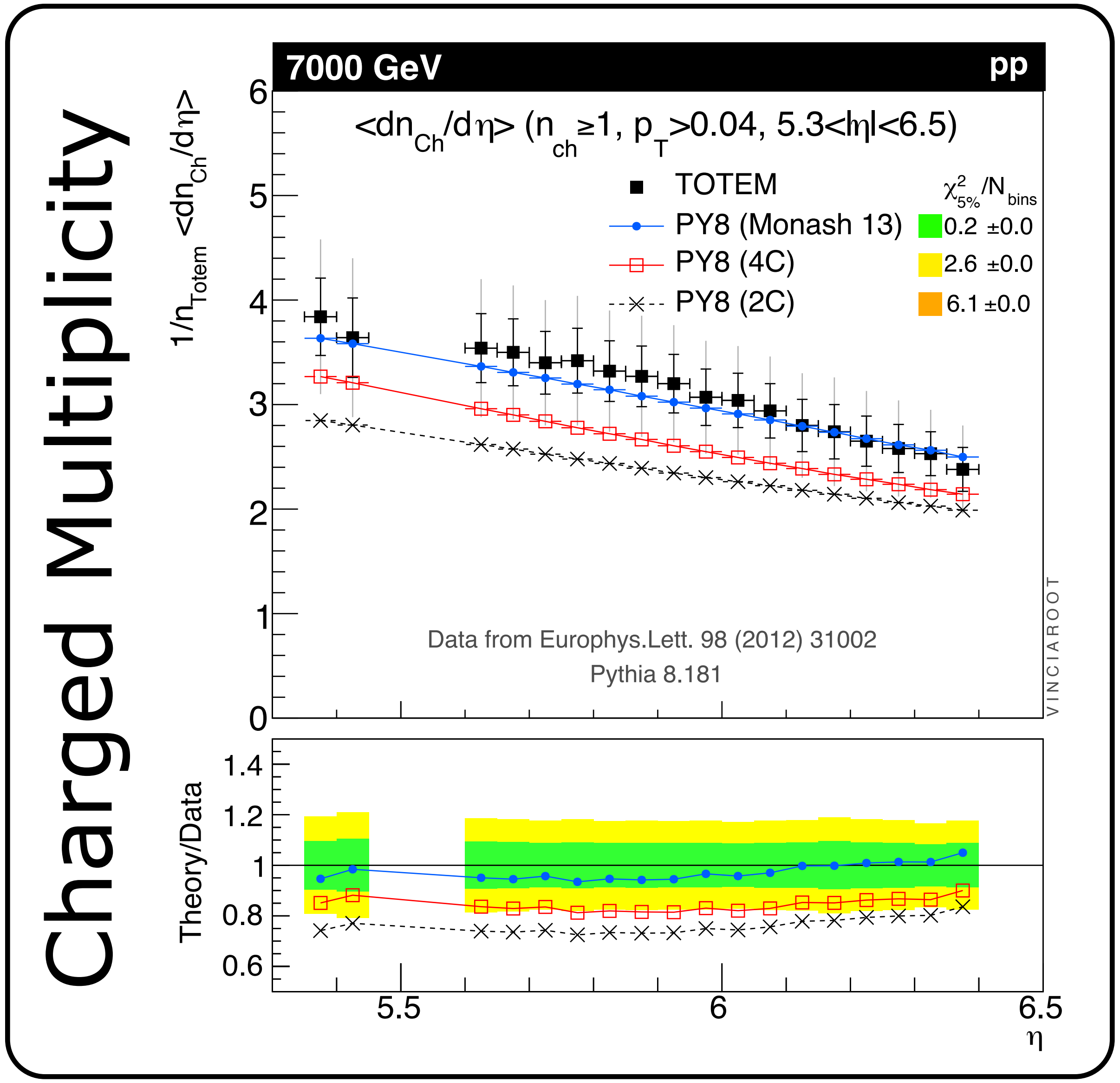


Plots from mcplots.cern.ch

The Forward Region

More sensitive to low x & diffraction





2C: an older Tevatron tune

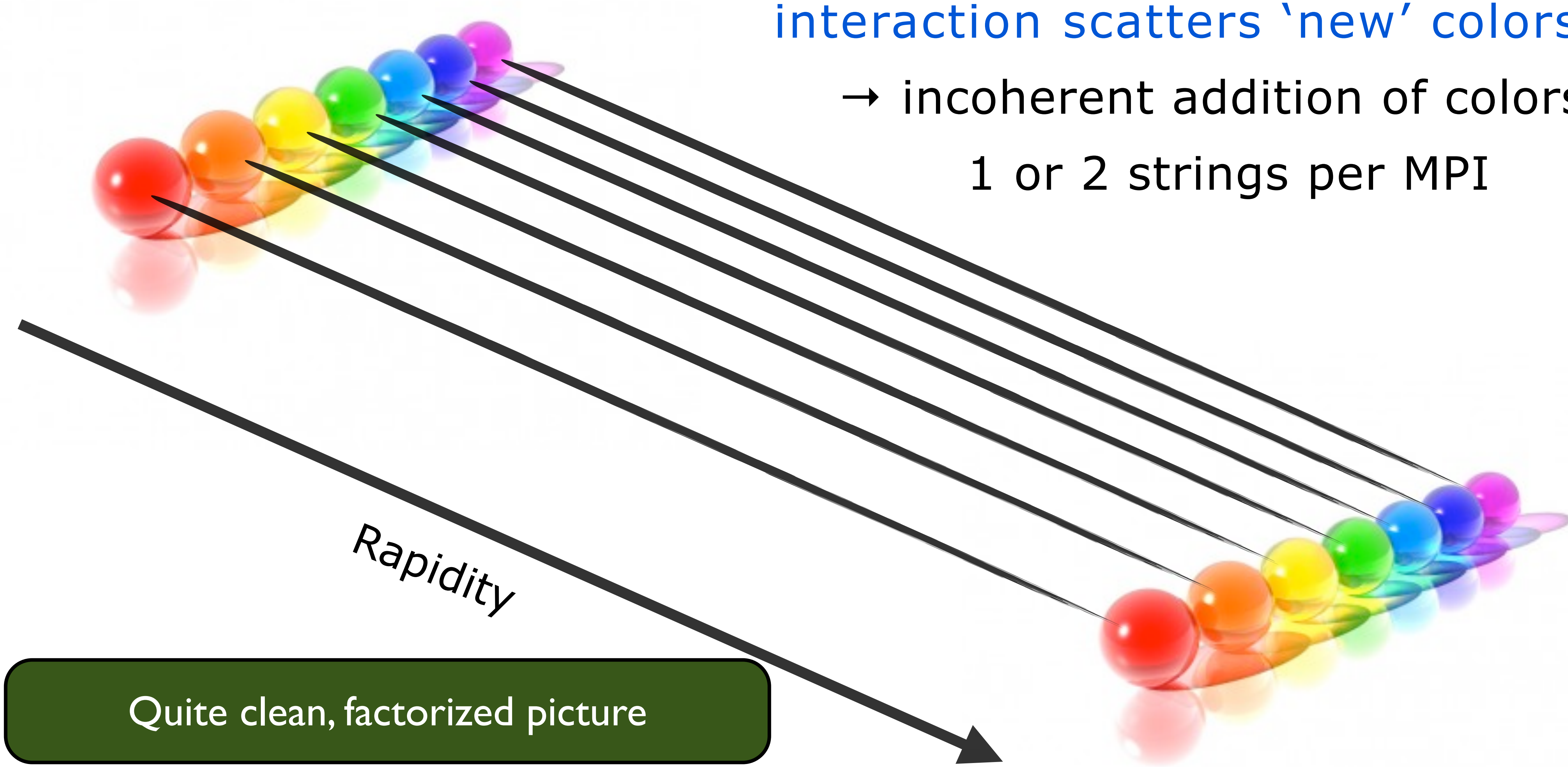
4C: the current LHC tune (Default in Pythia 8.1)

Monash 2013: a new LEP + LHC tune (Default from Pythia 8.2?)

Hadronization

color flow, color reconnections, particle spectra

Color Connections



Leading N_C: each parton-parton interaction scatters 'new' colors

→ incoherent addition of colors

1 or 2 strings per MPI

Quite clean, factorized picture

WRONG!

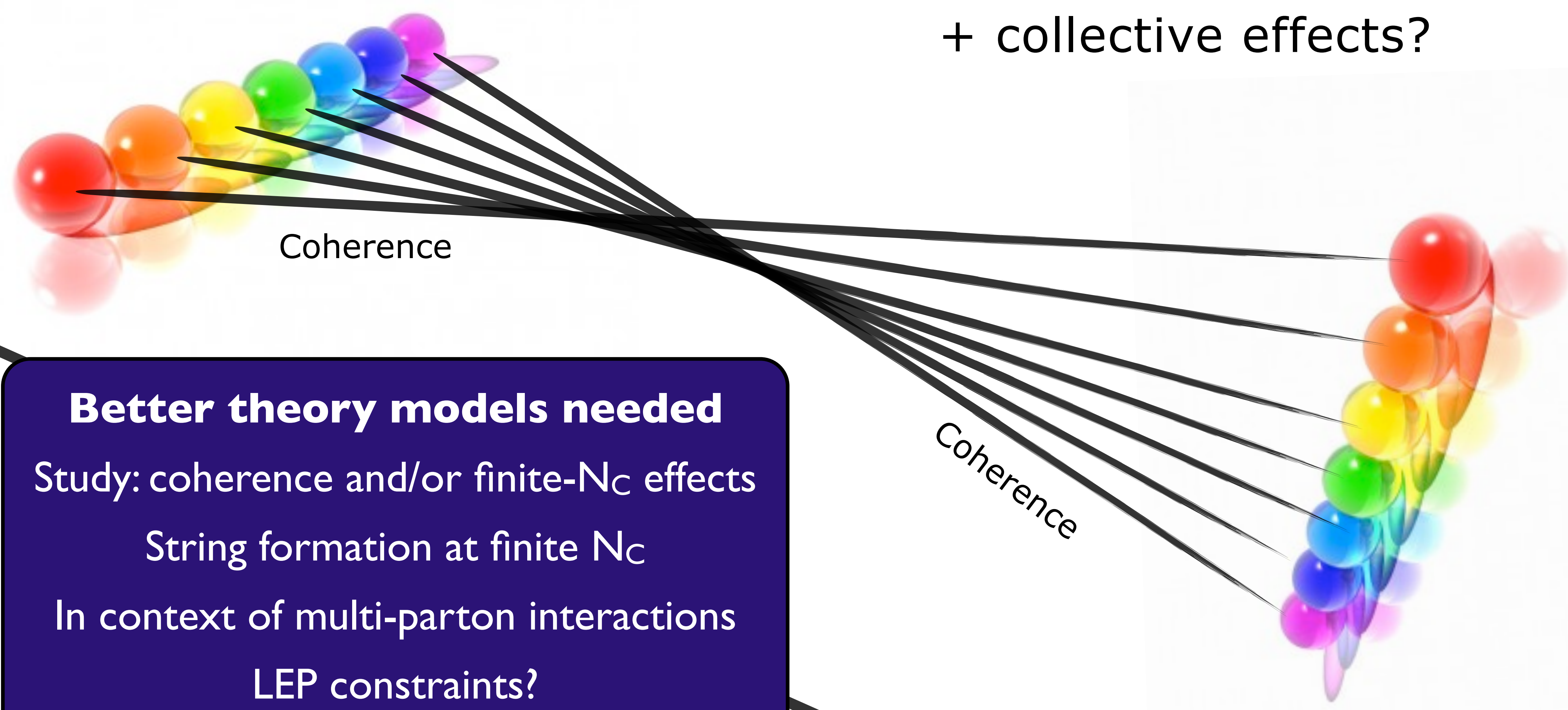
Multiplicity $\propto N_{MPI}$

Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (P.S., Wicke: Eur. Phys. J. C52 (2007) 133)
…

N_C=3: Colors add coherently

+ collective effects?



Better theory models needed

Study: coherence and/or finite-N_C effects

String formation at finite N_C

In context of multi-parton interactions

LEP constraints?

Additional collectivity? (a la HI? BE?)

Multiplicity $\not\propto$ (<) N_{MPI}

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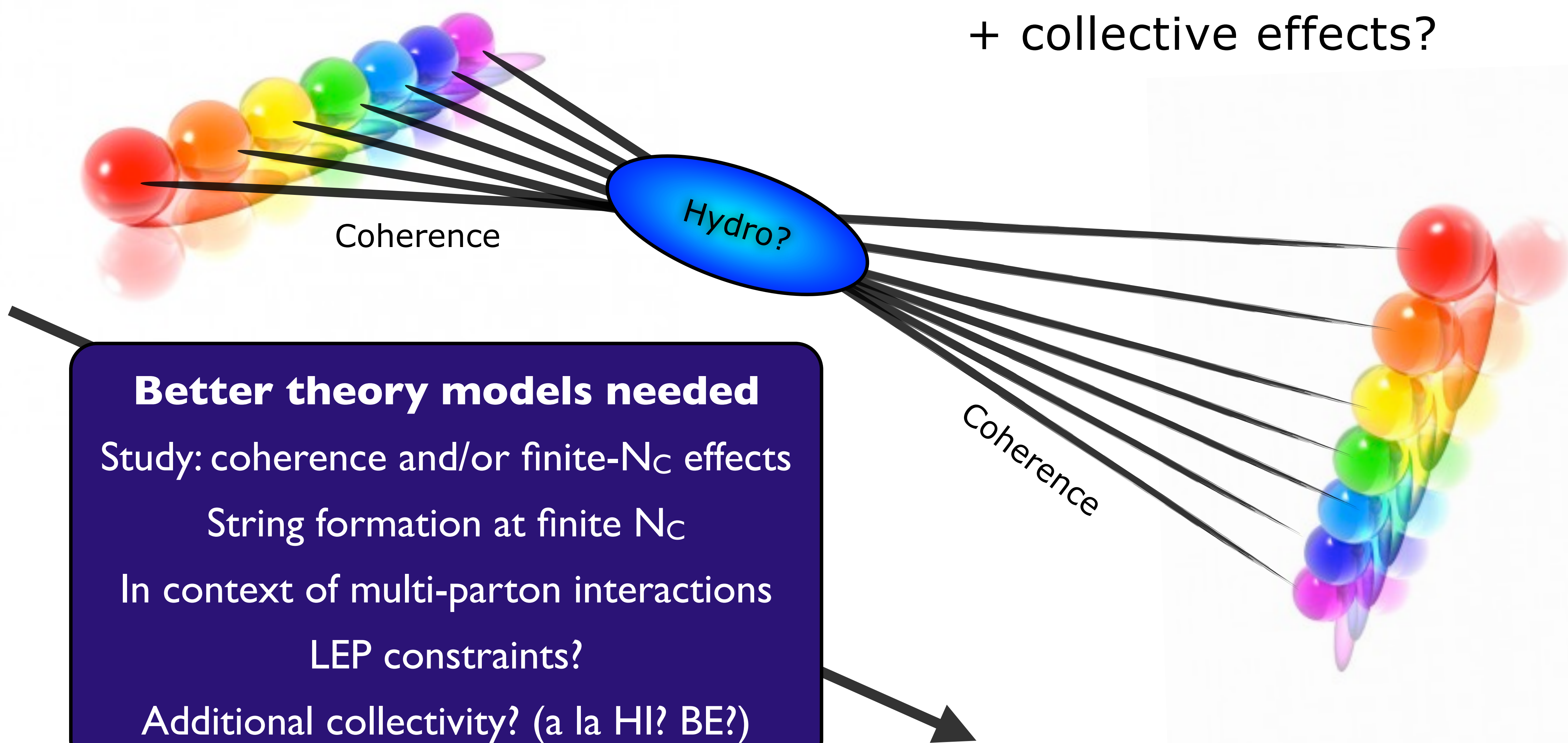

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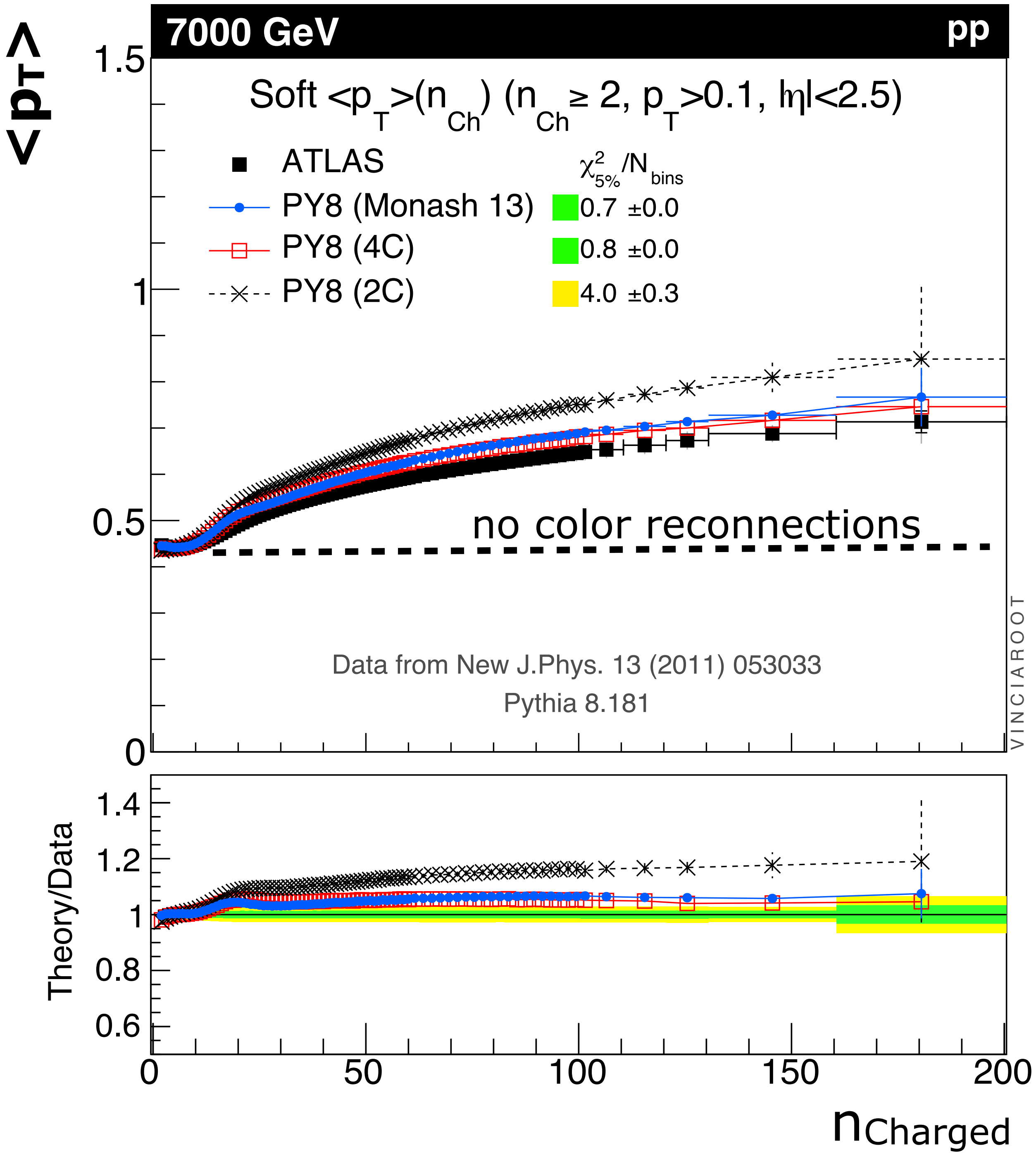
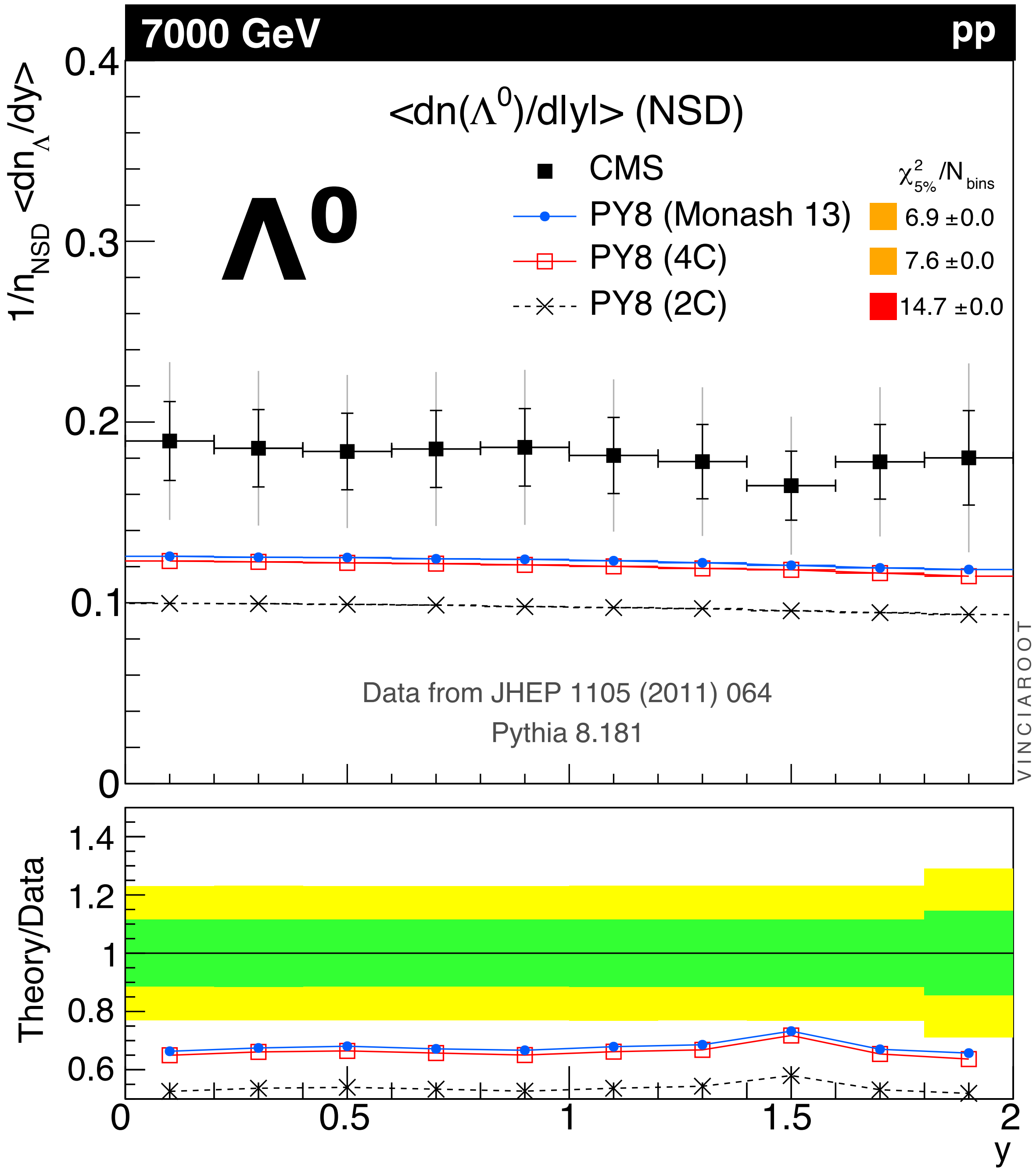
Signs of collectivity?

1) Rise of $<p_T>$ with multiplicity



2) Baryons by coalescence?



Gluon Splitting

Less singular than gluon emission: single log

$$P(g \to q\bar{q}) \propto \frac{1}{m_{q\bar{q}}^2}$$

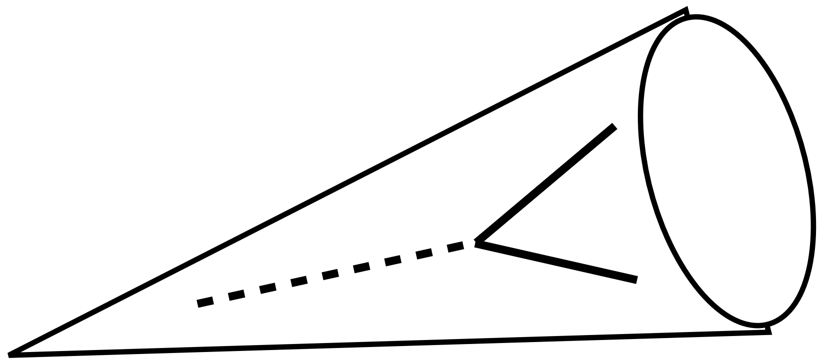
→ *Less* precise, from parton-shower viewpoint

Massive quarks → not even singular

Predictions for g→cc,bb differ greatly between models

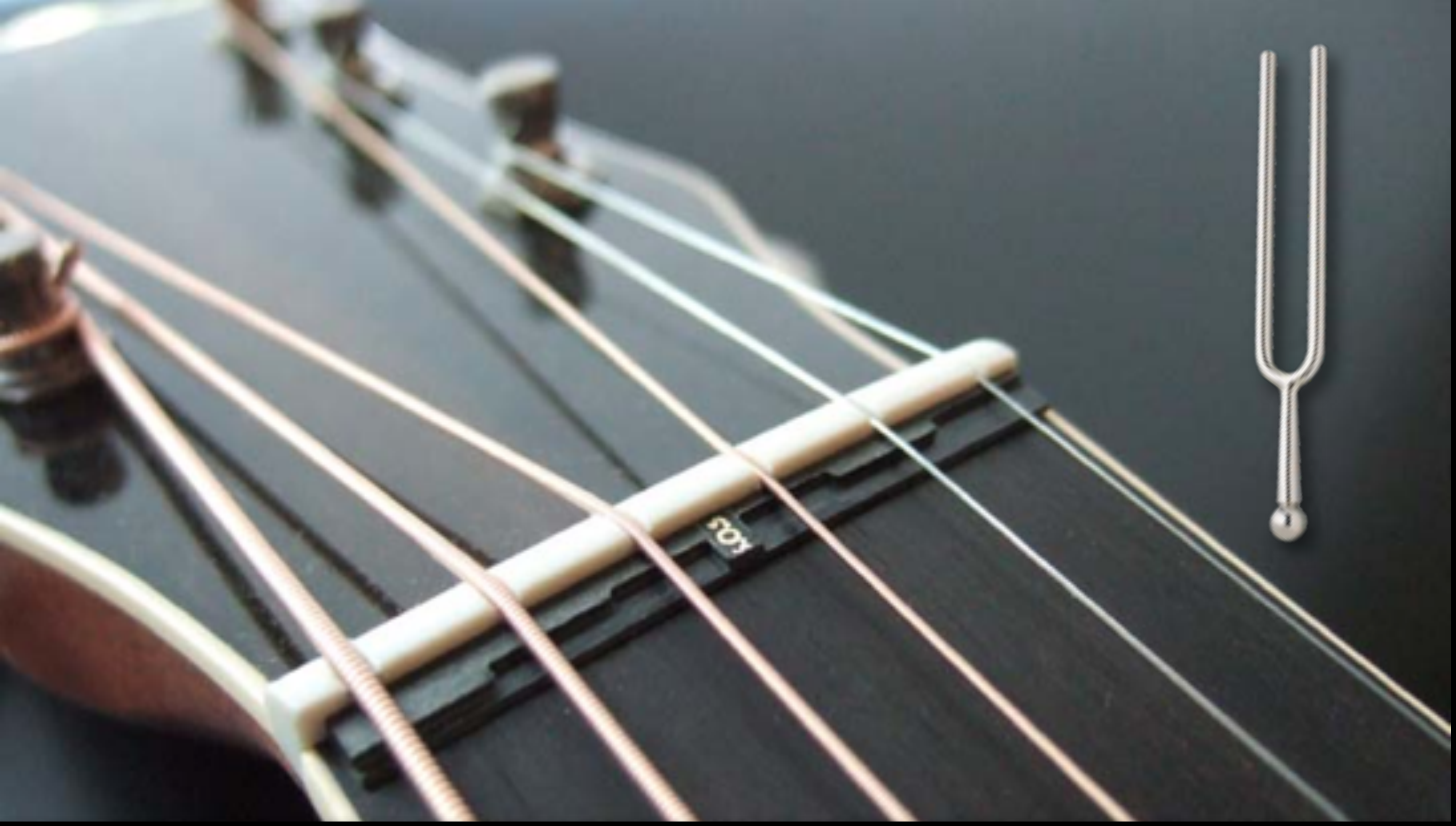
Non-singular terms, evolution variable, renormalization scale

Beware: overpredicted if (c,b) treated massless



Strong interest in constraints from double-tagged heavy-flavor jets

At the theory level we will learn more from NLO corrections to gluon-splitting processes



Tuning

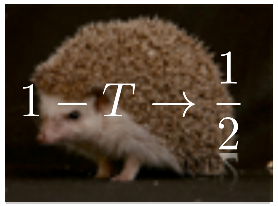
means different things to different people

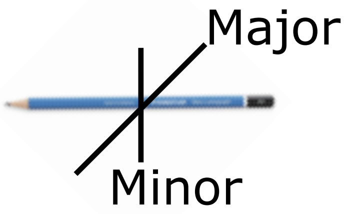
Example: Value of Strong Coupling

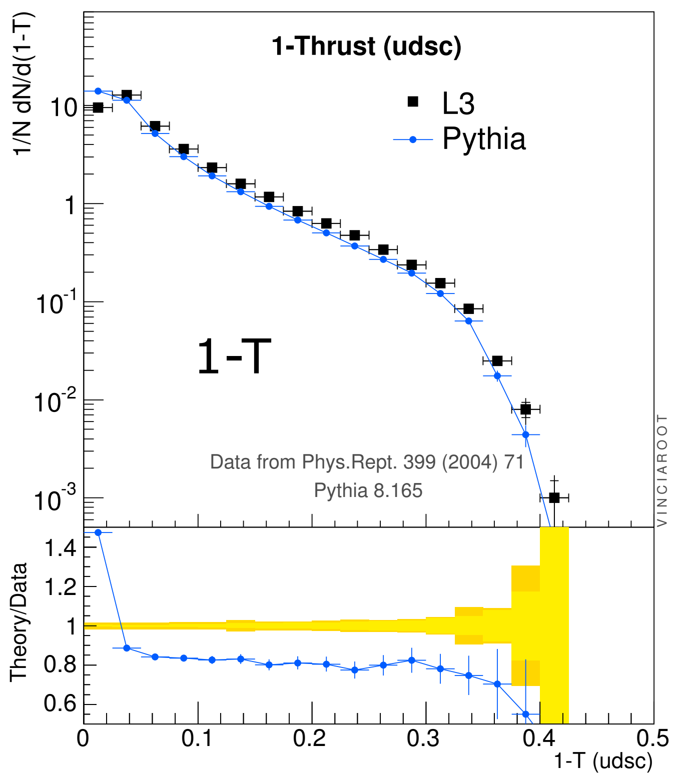
PYTHIA 8 (hadronization on) **vs LEP: Thrust**

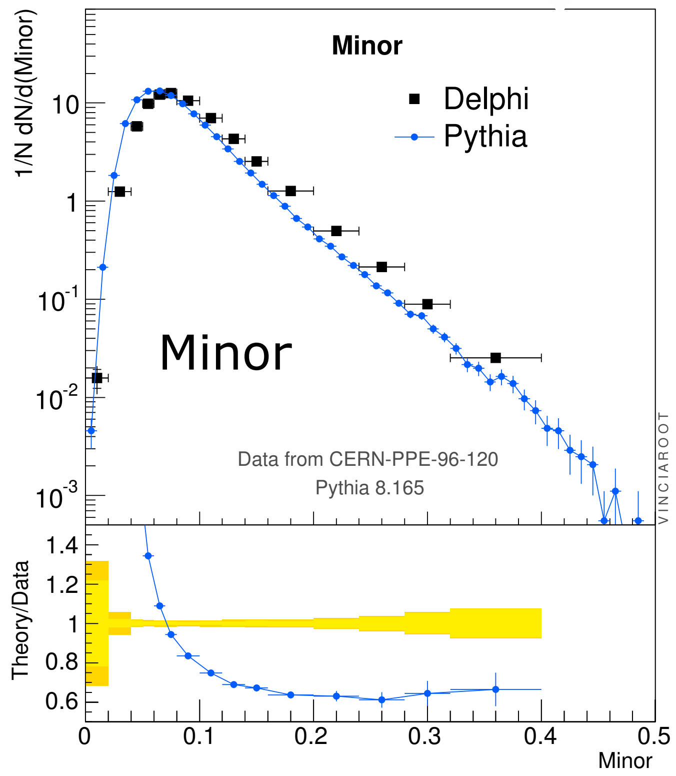
$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \right)$$

$1 - T \to 0$









$\alpha_s(M_Z) = 0.12$

1-loop running, MC

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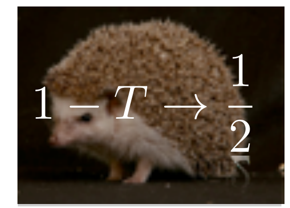

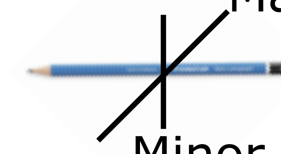

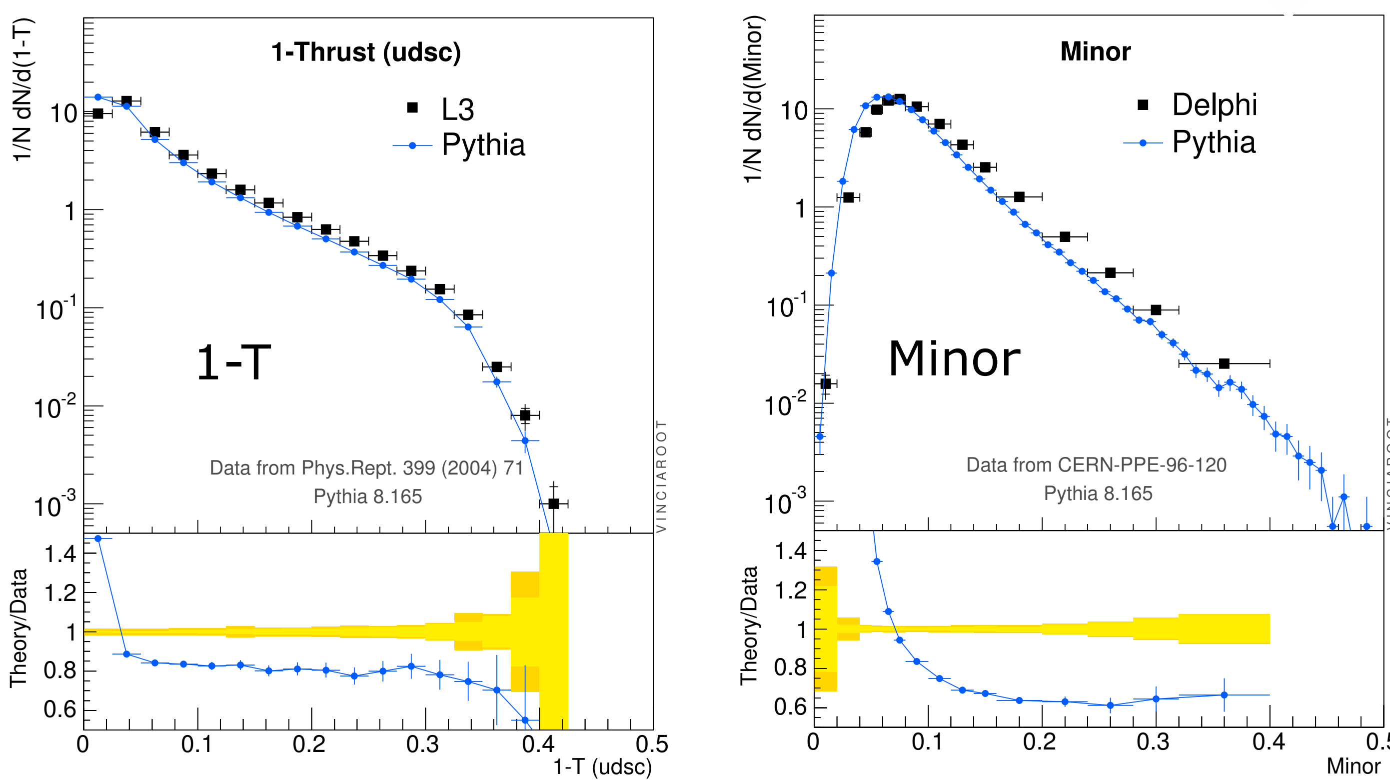

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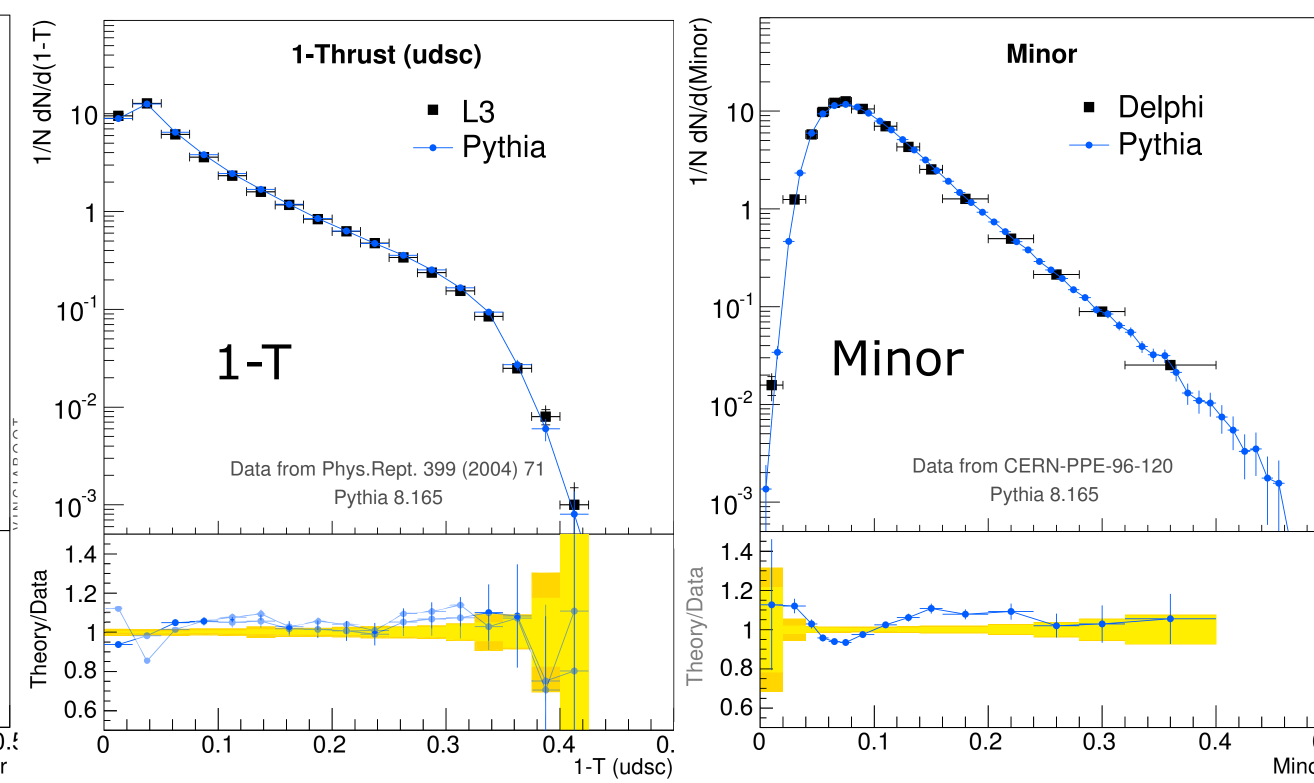


$\alpha_s(M_Z) = 0.14$
1-loop running, MC

+ IR regularization → Impact on non-perturbative parameters!

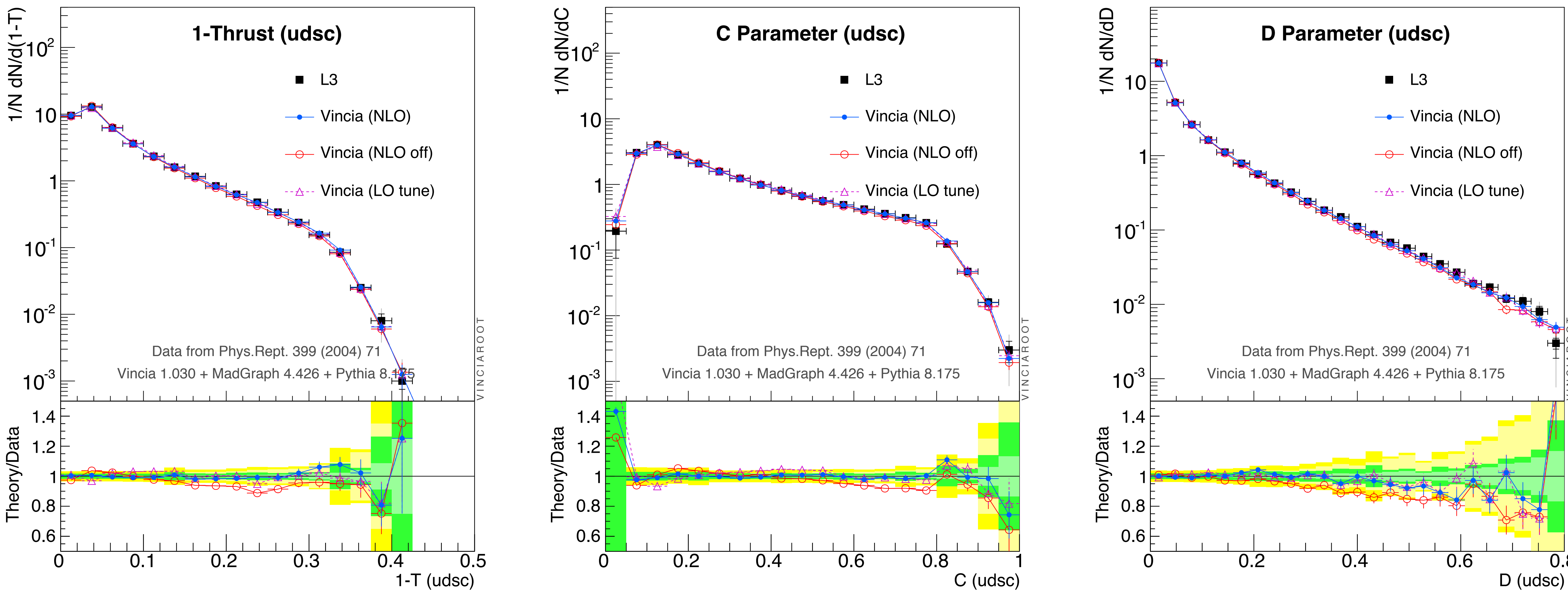
VINCIA: Multijet NLO Corrections

Hartgring, Laenen, Skands, arXiv:1303.4974

First LEP tune with NLO 3-jet corrections

LO tune: $\alpha_s(M_Z) = 0.139$ (1-loop running, MC)

NLO tune: $\alpha_s(M_Z) = 0.122$ (2-loop running, MSbar→MC)



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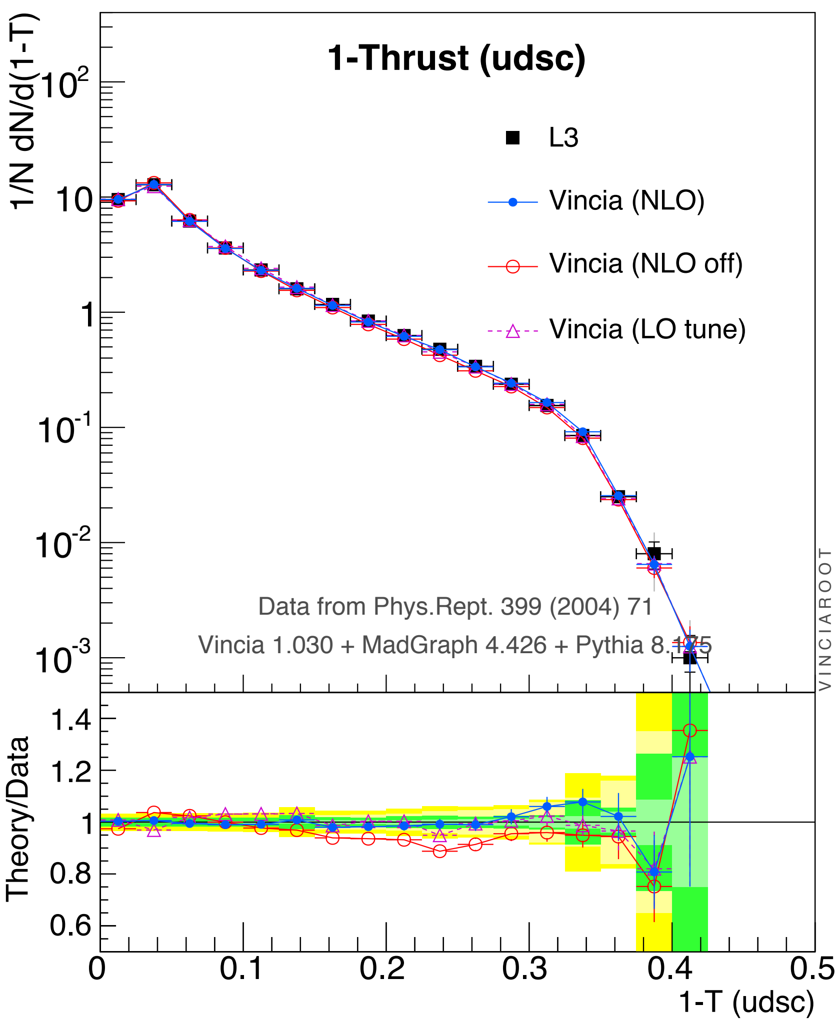

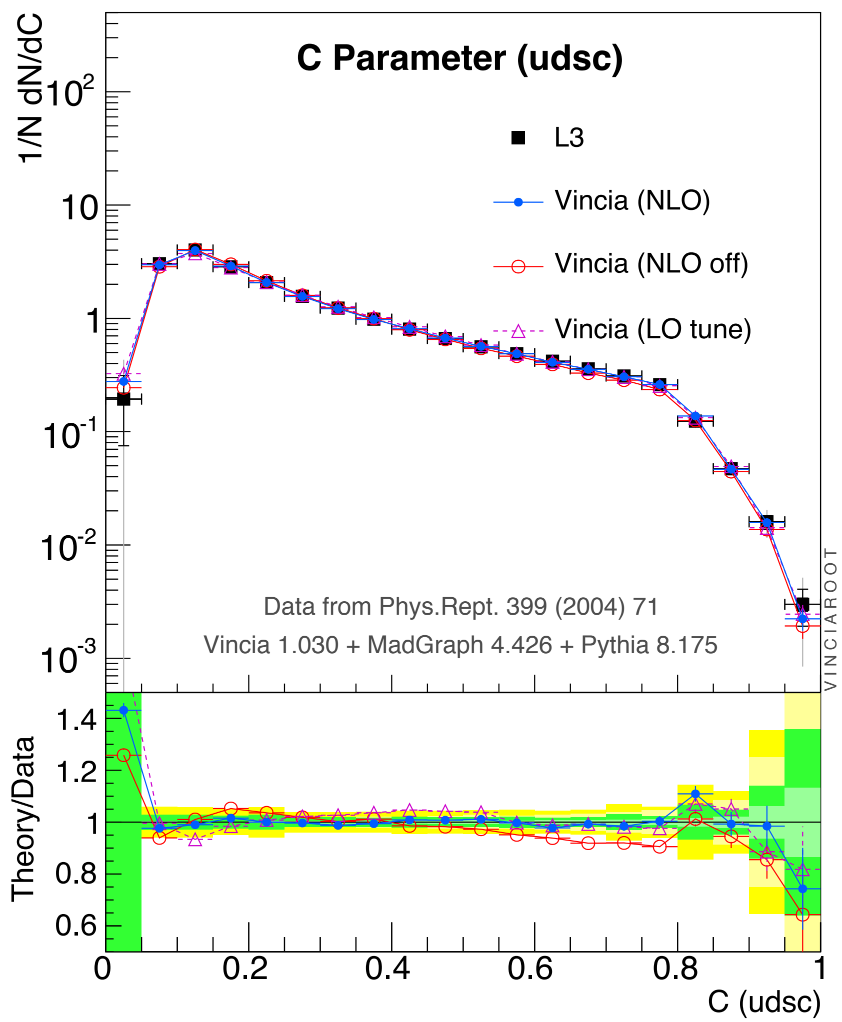

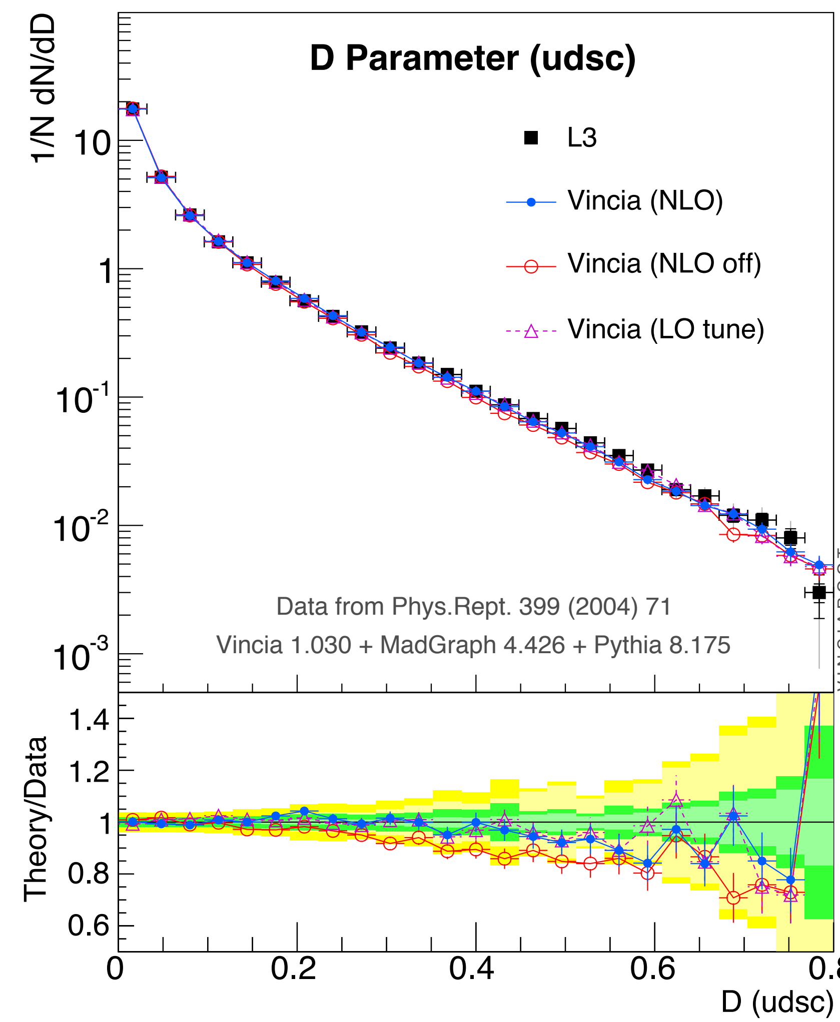

Soft QCD Models: Outlook

HERWIG++ and SHERPA are developing diffractive models + investigating color reconnections

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EPOS uses collective effects (hydro) also in pp

Impressive successes for identified-particle spectra (→?)

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PYTHIA 8 (by now generally superior to PYTHIA 6)

- New "Monash 2013" tune (LEP+MB+UE+DY) (from v.8.185)
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PHOJET, SIBYLL, QGSJET (pomeron-based)

- Personal (biased?) view: Problems with soft-to-hard transition

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Tuning: LO vs NLO & universality needs better understanding mcplots.cern.ch

Menu

- → Front Page
- → LHC@home 2.0
- → Generator Versions
- → Generator Validation
- → Update History
- → User Manual and Reference

Analysis filter:

- → ALL pp/ppbar
- → ALL ee

Specific analysis:

→

- → Latest analyses

Z (Drell-Yan)

- → Jet Multiplicities
- → $1/\sigma d\sigma(Z)/d\varphi^*_\eta$
- → $d\sigma(Z)/dpTZ$
- → $1/\sigma d\sigma(Z)/dpTZ$

W

- → Charge asymmetry vs η
- → Charge asymmetry vs N_{jet}
- → $d\sigma(jet)/dpT$
- → Jet Multiplicities

Top (MC only)

- → Δφ (ttbar)
- → Δy (ttbar)
- → |Δy| (ttbar)
- → M (ttbar)
- → pT (ttbar)
- → Cross sections
- → y (ttbar)
- → Asymmetry
- → Individual tops

Bottom

- → η Distributions
- → pT Distributions
- → Cross sections

Jets

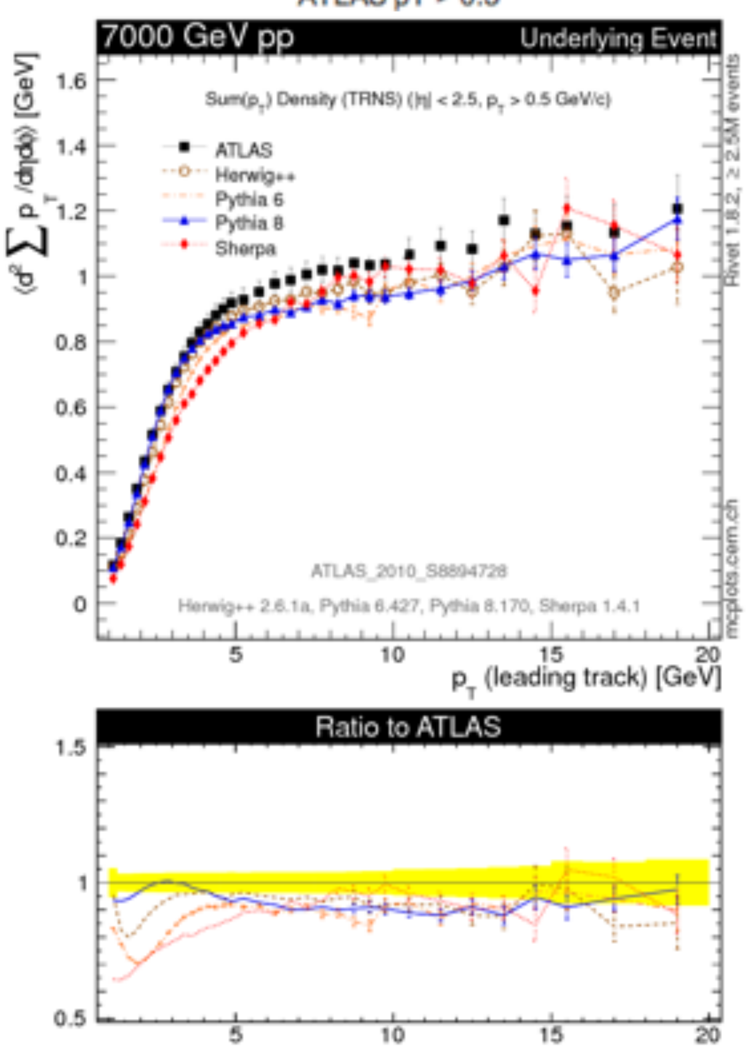
Underlying Event : TRNS : Σ(pT) vs pT1

Generator Group: General-Purpose MCs Soft-Inclusive MCs Alpgen Herwig++ Pythia 6 Pythia 8 Sherpa Vincia Epos Phojet Custom

Subgroup: Defaults LHC Tunes C++ Generators Tevatron vs LHC tunes

pp @ 7000 GeV

ATLAS pT > 0.5



[pdf] [eps] [png] hide details ←

[ATLAS] reference

[Herwig++ (Def)] param

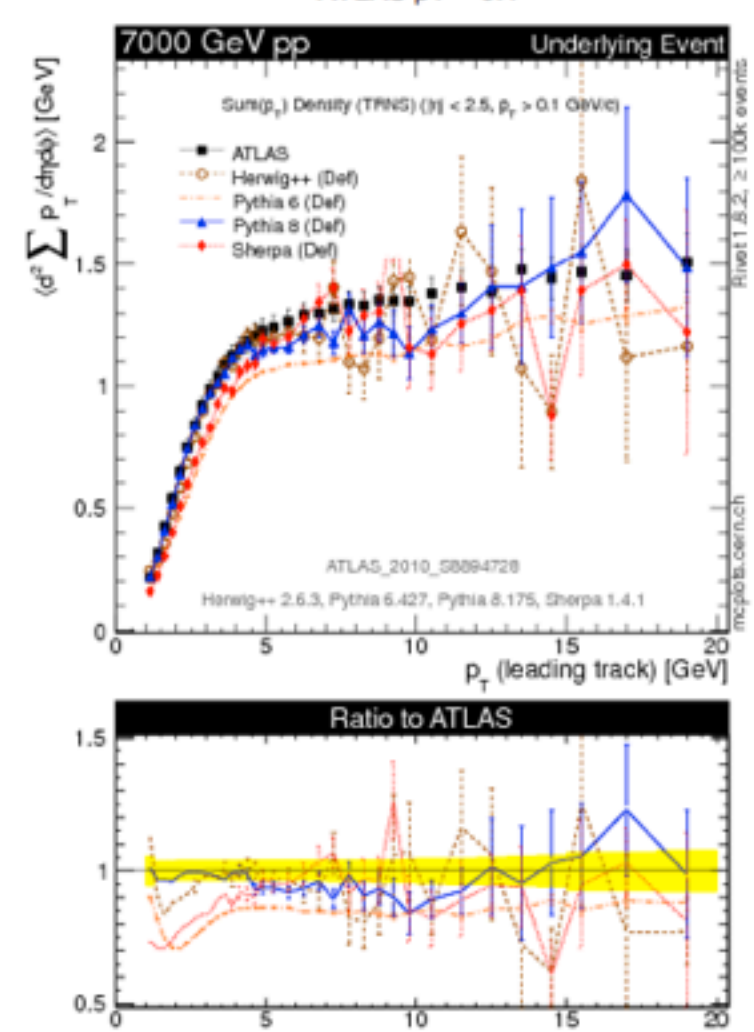
[Pythia 6 (Def)] param

[Pythia 8 (Def)] param

[Sherpa (Def)] param

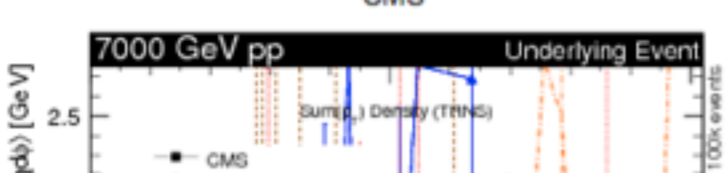
[steer]

ATLAS pT > 0.1



[pdf] [eps] [png] show details →

CMS



- Explicit tables of data & MC points
- Run cards for each generator
- Link to experimental reference paper
- Steering file for plotting program
- (Will also add link to RIVET analysis)

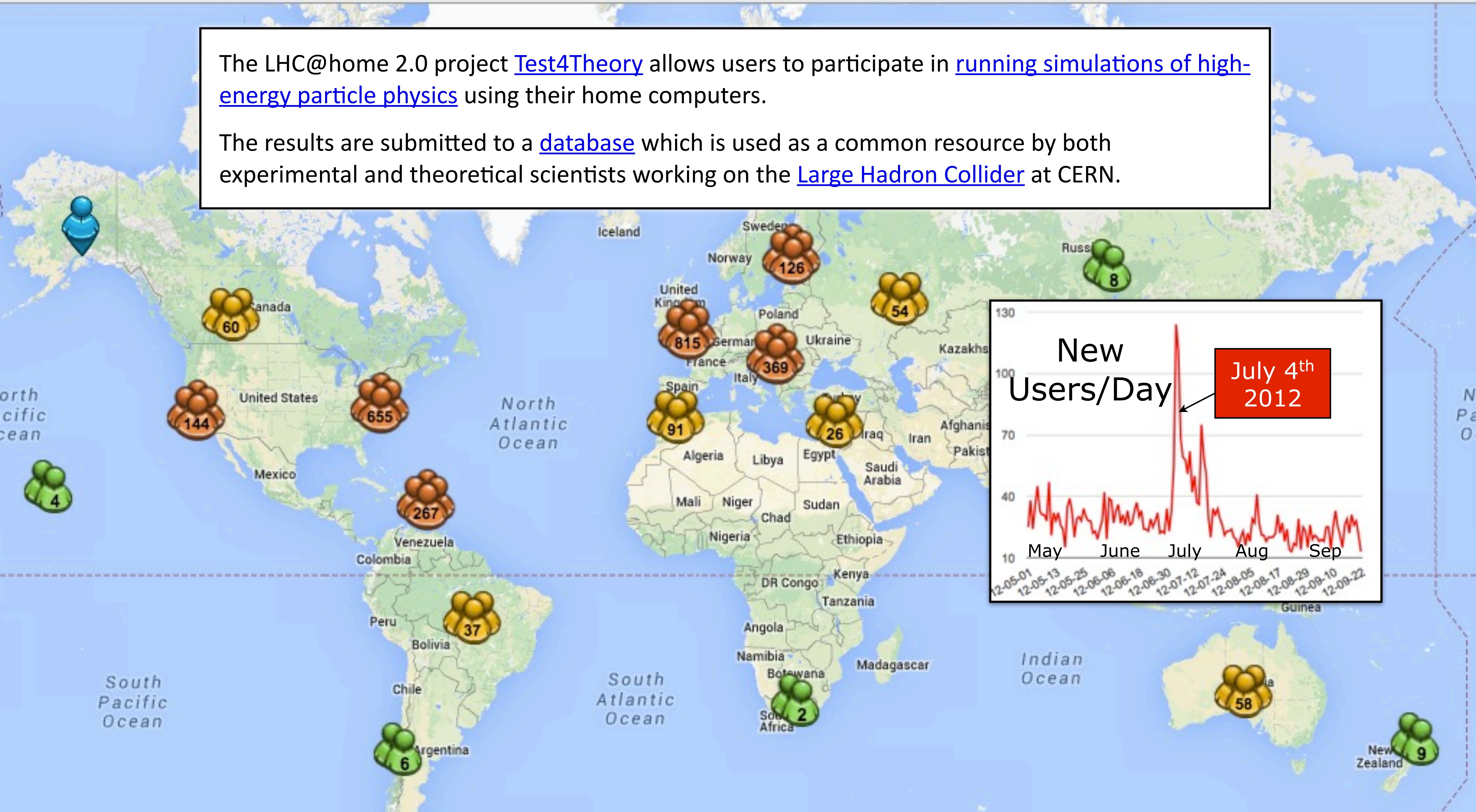
Test4Theory - LHC@home

http://lhcathome.cern.ch/test4theory

LHC@home 2.0 Test4Theory volunteers' machines seen since Sun Nov 17 2013 14:00:00 GMT+1100 (EST) (2804 machines overall)

The LHC@home 2.0 project Test4Theory allows users to participate in running simulations of high-energy particle physics using their home computers.

The results are submitted to a database which is used as a common resource by both experimental and theoretical scientists working on the Large Hadron Collider at CERN.



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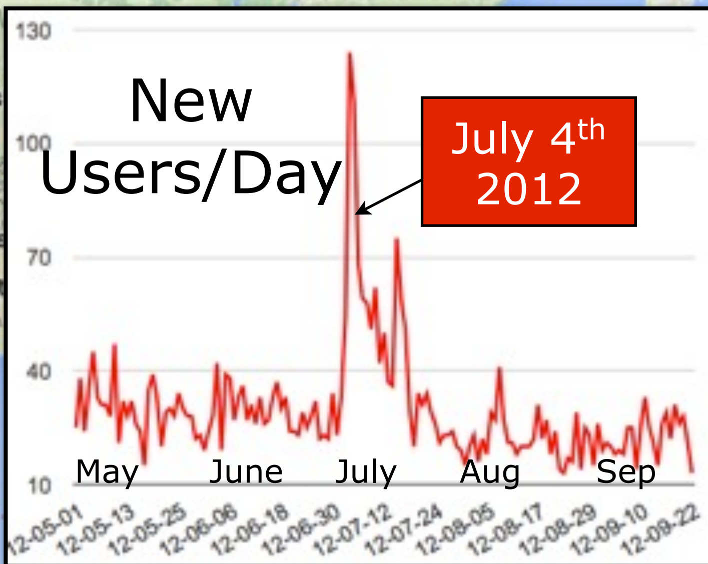
New: *Citizen Cyberlab* (funds from EU)

Develop an app that lets citizen scientists **learn about, interact with, and optimize high-energy physics simulations**, by **comparing them to real data**



Come to Australia

p p

Establishing a new group in **Melbourne**

Working on **PYTHIA** & **VINCIA**

NLO Event Generators

Precision LHC **phenomenology & soft physics**

Support LHC **experiments**, **astro-particle** community, and **future** accelerators

Outreach and Citizen Science

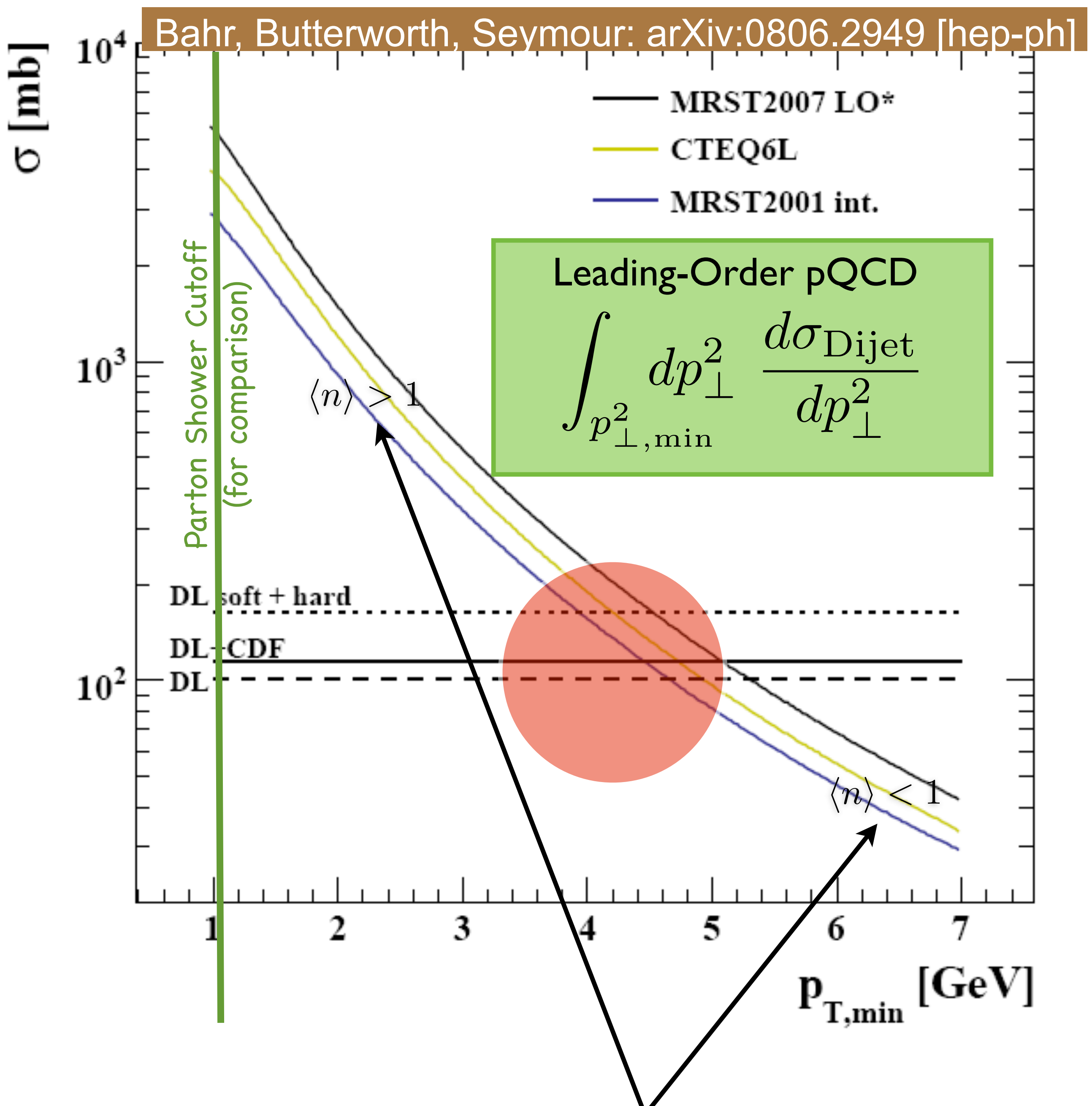
Oct 2014

→ Monash University

Melbourne, Australia

Multiple Interactions

= Allow several parton-parton interactions per hadron-hadron collision. Requires extended factorization ansatz.

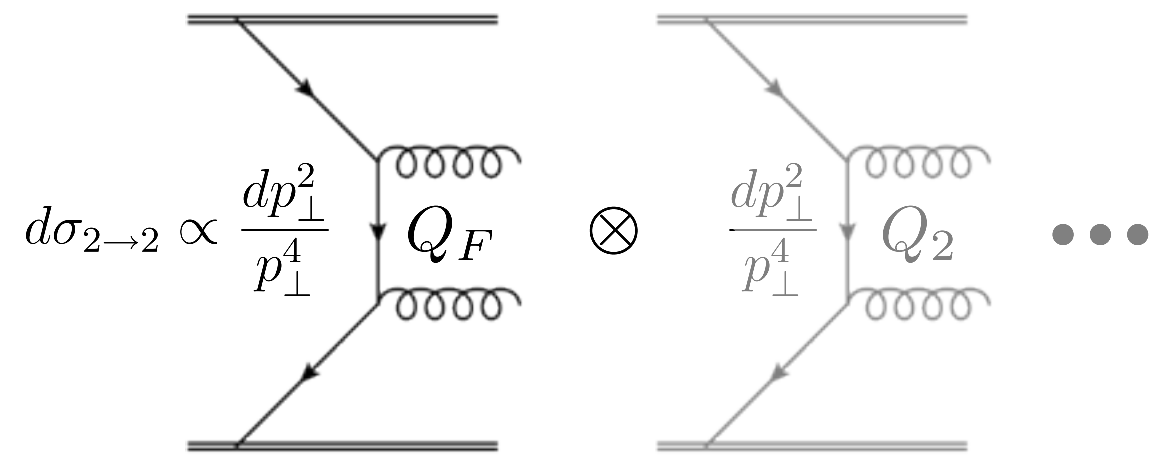


$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\rm tot}$$

Parton-Parton Cross Section

Hadron-Hadron Cross Section

Earliest MC model ("old" PYTHIA 6 model)
Sjöstrand, van Zijl PRD36 (1987) 2019



Lesson from bremsstrahlung in pQCD: divergences → fixed-order breaks down

Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

How many?

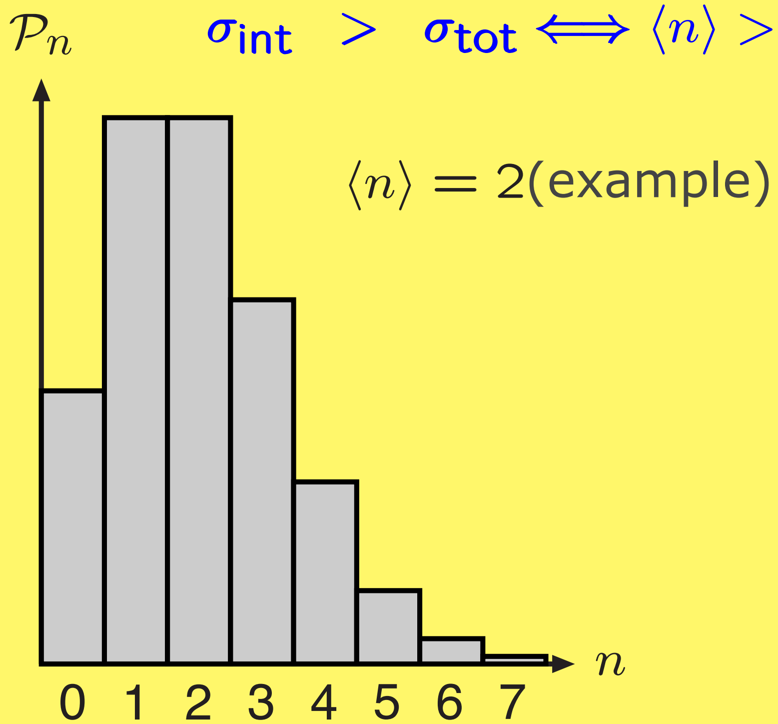
Naively $\langle n_{2\to2}(p_{\perp\min})\rangle = \dfrac{\sigma_{2\to2}(p_{\perp\min})}{\sigma_{\rm tot}}$

Interactions independent (naive factorization) → Poisson

$$\sigma_{\rm tot} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\rm int} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\sigma_{\rm int} > \sigma_{\rm tot} \iff \langle n\rangle > 1$$



$$\mathcal{P}_n = \frac{\langle n\rangle^n}{n!}\, e^{-\langle n\rangle}$$

Real Life

Momentum conservation suppresses high-n tail

+ physical correlations

→ not simple product

1: A Simple Model

The minimal model incorporating single-parton factorization, perturbative unitarity, and energy-and-momentum conservation

$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n\rangle(p_{\perp\min})\ \sigma_{\rm tot}$$

Parton-Parton Cross Section   Hadron-Hadron Cross Section

1. Choose $p_{T\min}$ cutoff
   = main tuning parameter

2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton

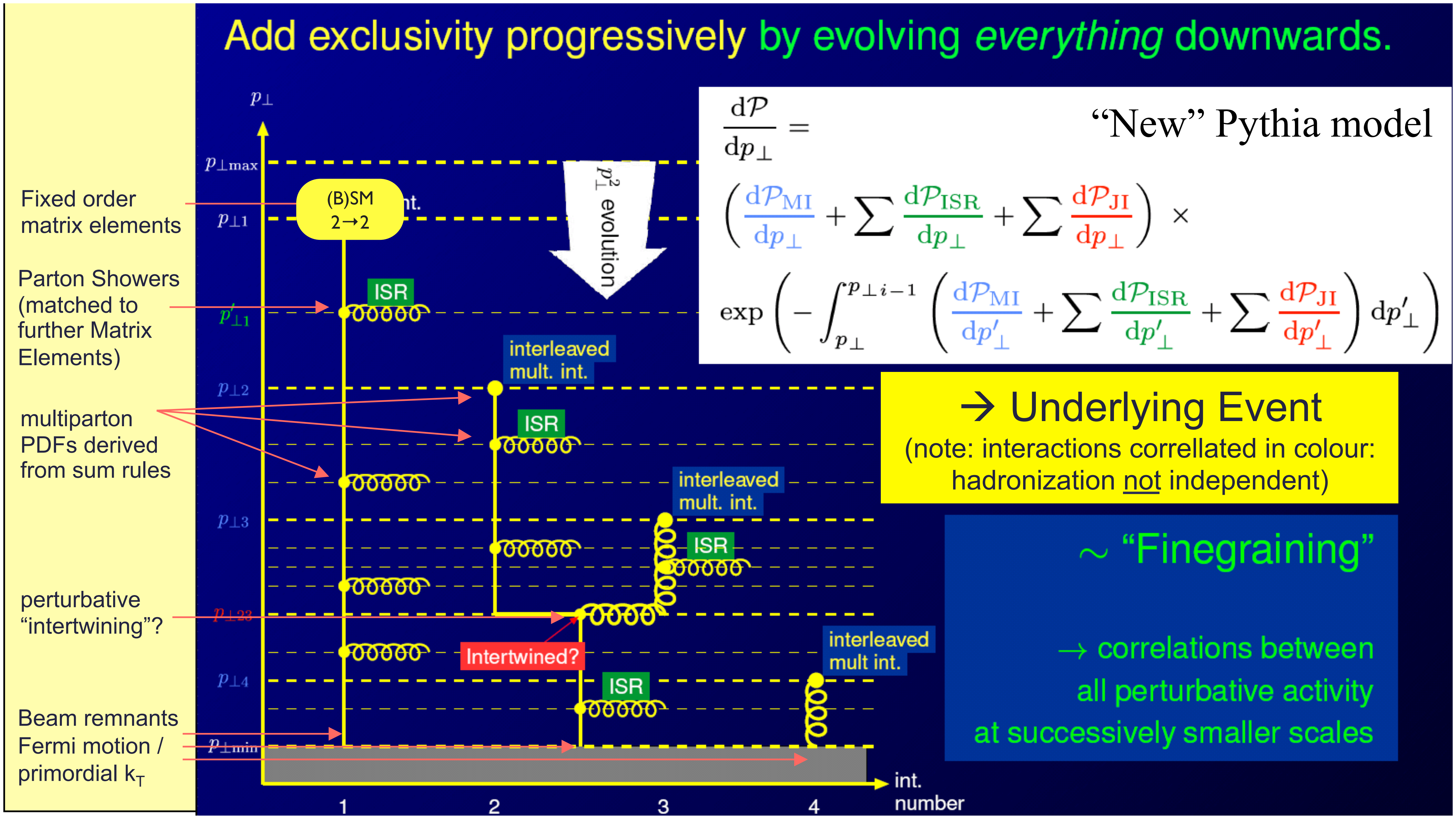
3. Generate n parton-parton interactions (pQCD 2→2)
   Veto if total beam momentum exceeded → overall (E,p) cons

4. Add impact-parameter dependence → $<n> = <n>(b)$
   Assume factorization of transverse and longitudinal d.o.f., → PDFs : $f(x,b) = f(x)g(b)$ (Ordinary CTEQ, MSTW, NNPDF, …)
   b distribution ∝ EM form factor → **JIMMY model** Butterworth, Forshaw, Seymour Z.Phys. C72 (1996) 637
   Constant of proportionality = second main tuning parameter

5. Add separate class of "soft" (zero-p_T) interactions representing interactions with $p_T < p_{T\min}$ and require $\sigma_{\rm soft} + \sigma_{\rm hard} = \sigma_{\rm tot}$
   → **Herwig++ model** Bähr et al, arXiv:0905.4671

2: Interleaved Evolution

Sjöstrand & Skands, JHEP 0403 (2004) 053; EPJ C39 (2005) 129

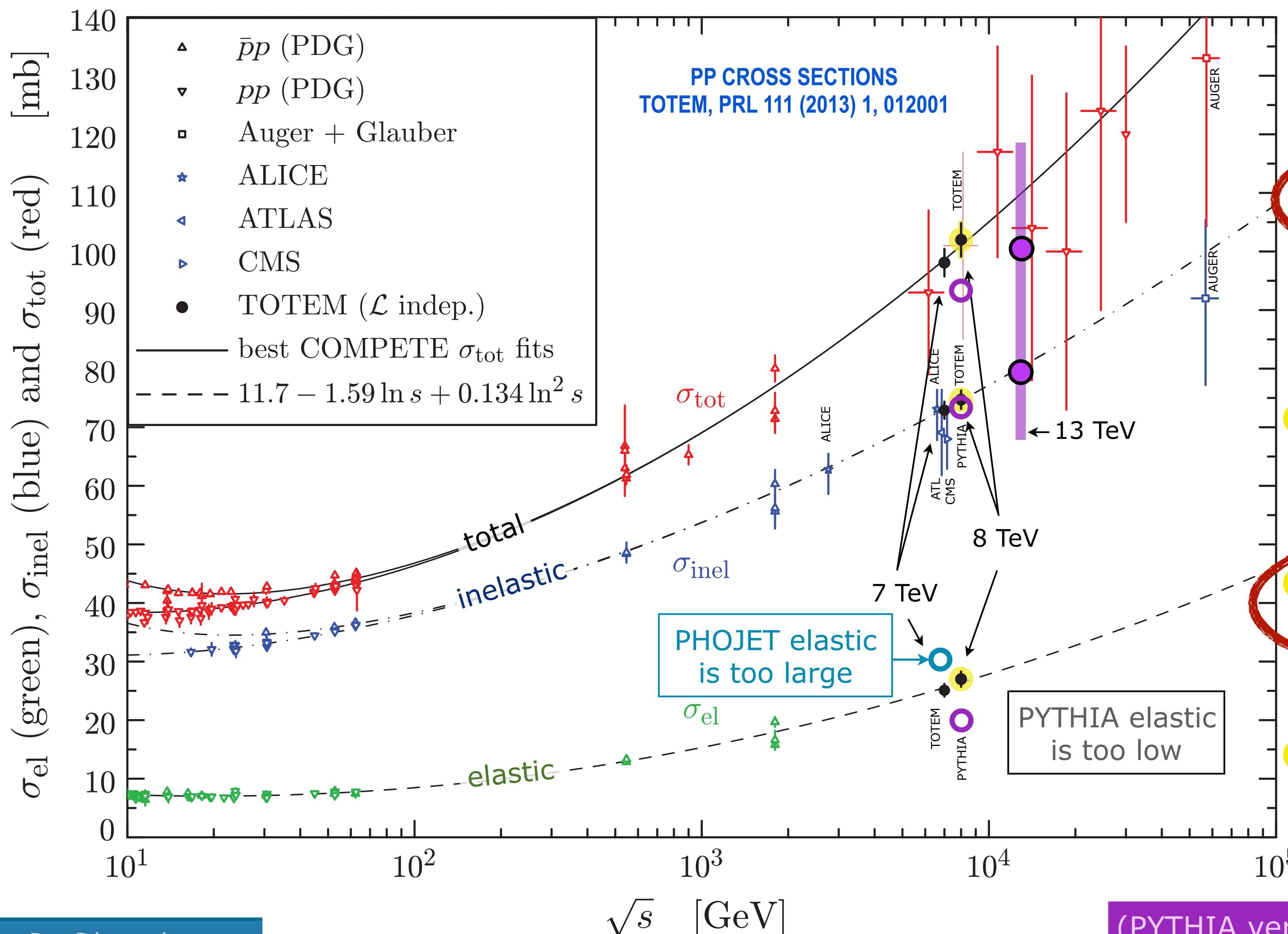


Also available for Pomeron-Proton collisions since Pythia 8.165

PHOJET elastic

$$\text{Pileup rate} \propto \sigma_{\text{tot}}(s) = \sigma_{\text{el}}(s) + \sigma_{\text{inel}}(s) \propto s^{0.08} \text{ or } \ln^2(s)\ ?$$

Donnachie-Landshoff | Froissart-Martin Bound



$\sigma_{\text{tot}}(13\ \text{TeV}) \sim 110 \pm 6$ mb

PYTHIA: 100 mb

$\sigma_{\text{inel}}(13\ \text{TeV}) \sim 80 \pm 3.5$ mb

PYTHIA: 78 mb

(2.9%)

$\sigma_{\text{tot}}(8\ \text{TeV}) = 101 \pm 2.9$ mb

PYTHIA: 93 mb

(2.3%)

$\sigma_{\text{inel}}(8\ \text{TeV}) = 74.7 \pm 1.7$ mb

PYTHIA: 73 mb

(5.1%)

$\sigma_{\text{el}}(8\ \text{TeV}) = 27.1 \pm 1.4$ mb

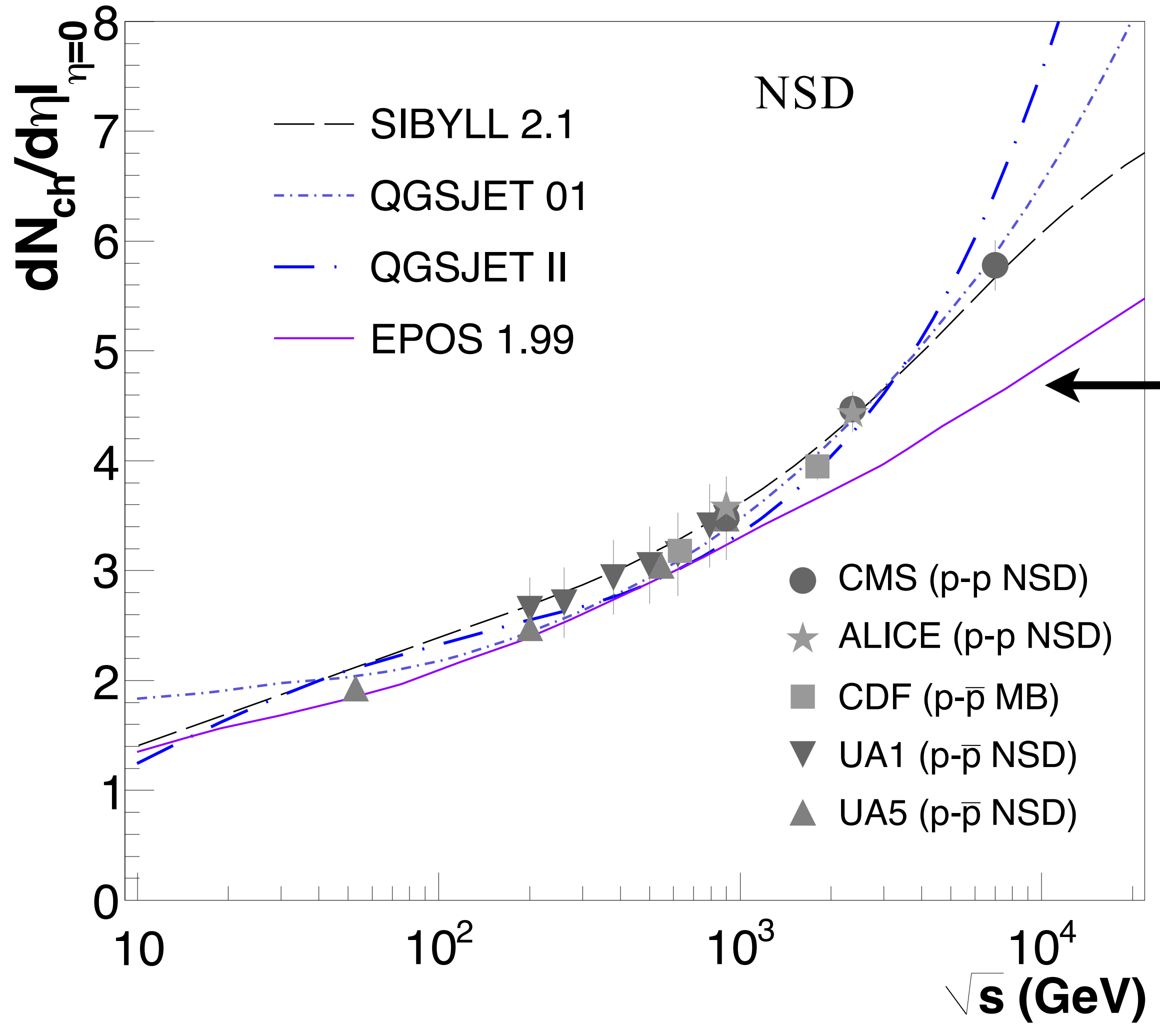
PYTHIA: 20 mb

(PYTHIA versions: 6.4.28 & 8.1.80)

Scaling of Multiplicities

A From soft models based on Regge Theory, expect: D. d'Enterria et al. [arXiv:1101.5596],

$$\left.\frac{dN_{\rm ch}(s,\eta)}{d\eta}\right|_{\eta=0} \propto \frac{{\rm Im} f^{\mathbb{P}}(s,0)}{s\,\sigma_{pp}^{\rm inel}(s)} \sim \frac{s^{\Delta_{\mathbb{P}}}}{\log^2 s},$$

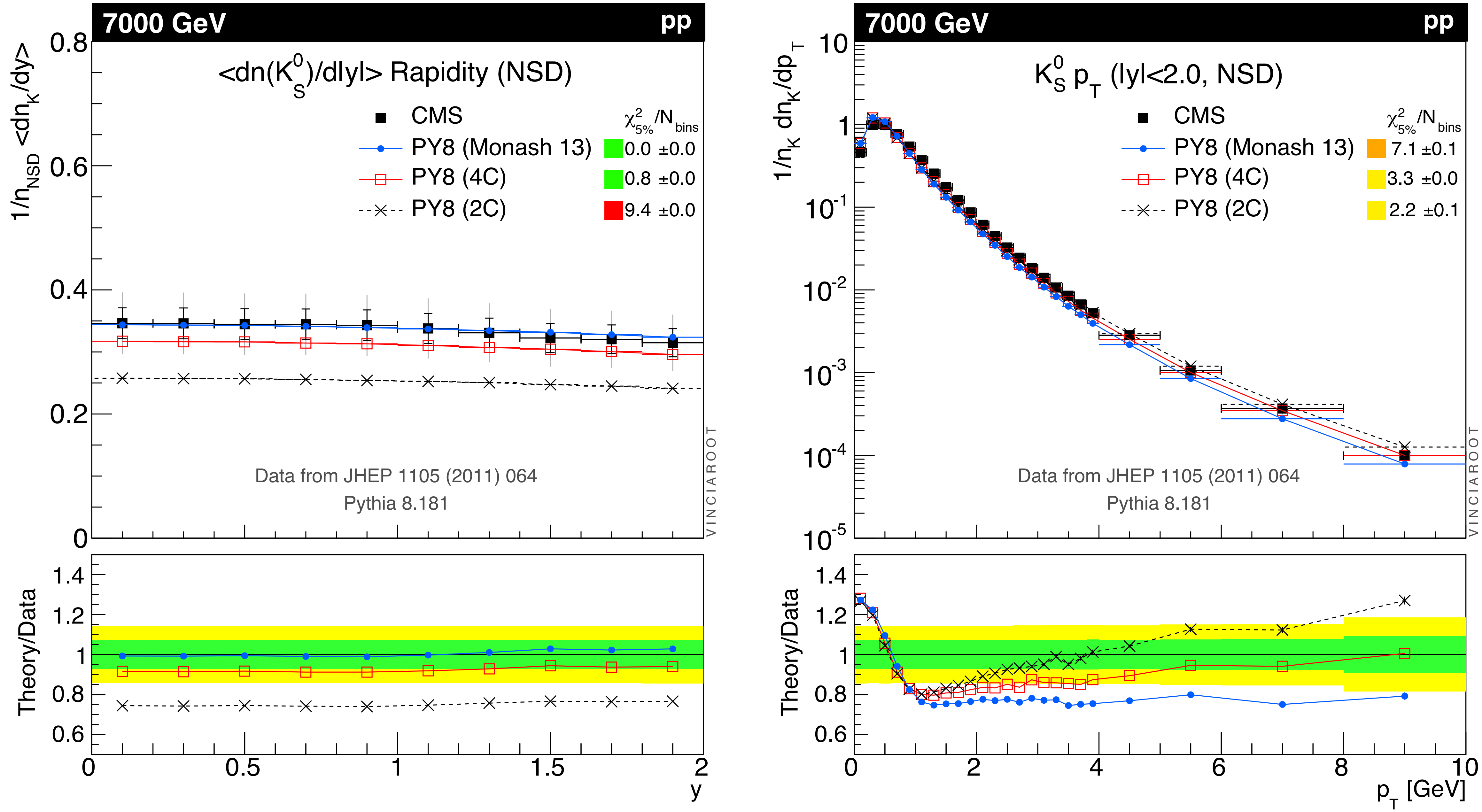


QGSJET too agressive? Would predict very high densities

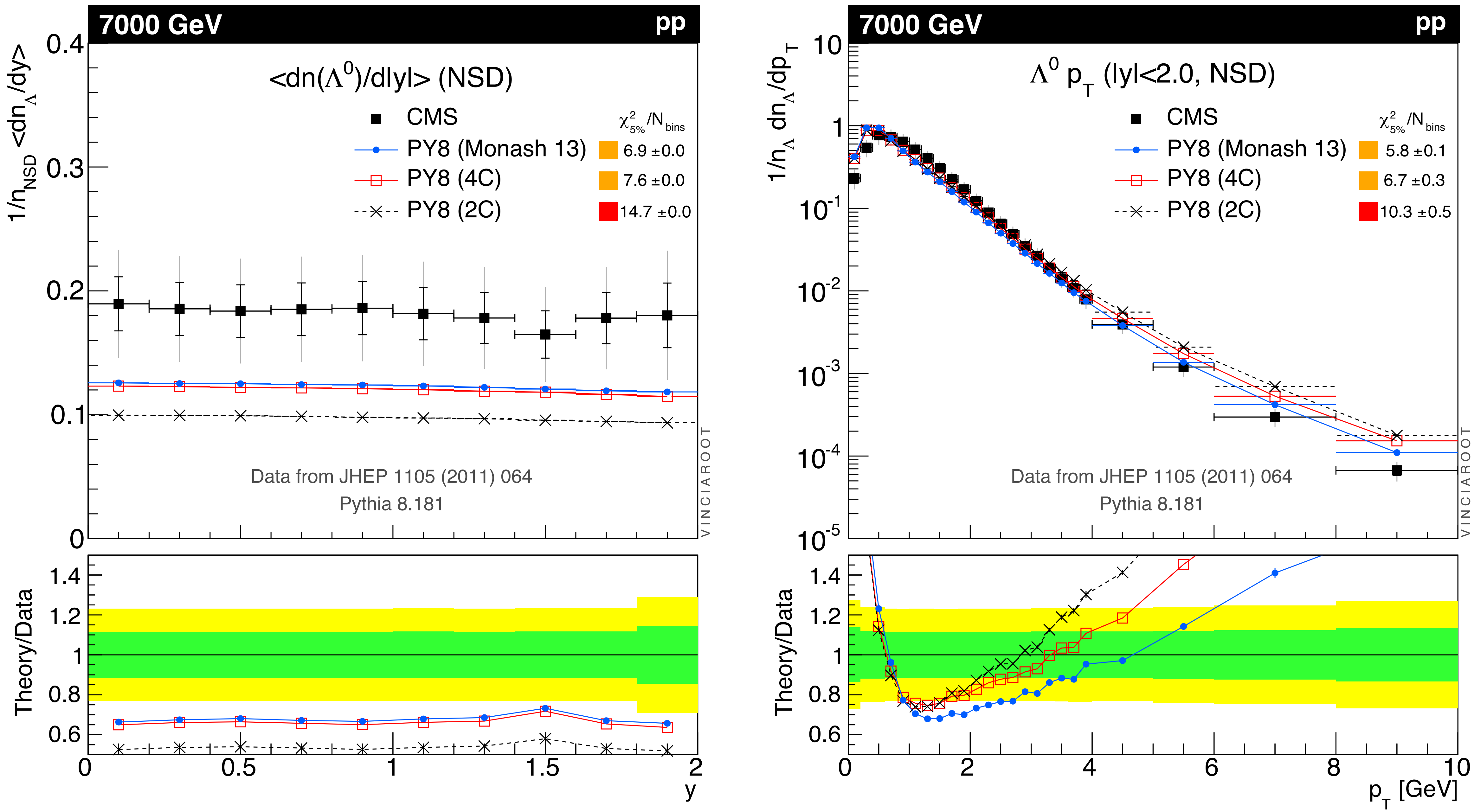
EPOS too low (but there is coming a new version which fits LHC better, worth trying out)

Will keep these models in mind but will base main extrapolations on PYTHIA Perugia tunes

Strangeness: Kaons



Strangeness: Λ hyperons



Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894

Diffractive Cross Section Formulæ:

$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\, \beta_{A\mathbb{P}}^2\, \beta_{B\mathbb{P}}\, \frac{1}{M^2}\, \exp(B_{sd(AX)}t)\, F_{sd}\,,$$

$$\frac{d\sigma_{dd}(s)}{dt\, dM_1^2\, dM_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\, \beta_{A\mathbb{P}}\, \beta_{B\mathbb{P}}\, \frac{1}{M_1^2}\, \frac{1}{M_2^2}\, \exp(B_{dd}t)\, F_{dd}\,.$$

$M_X \leq$ 10 GeV (and for all masses in PYTHIA 6)

Represent M_X as longitudinal string → Fragment

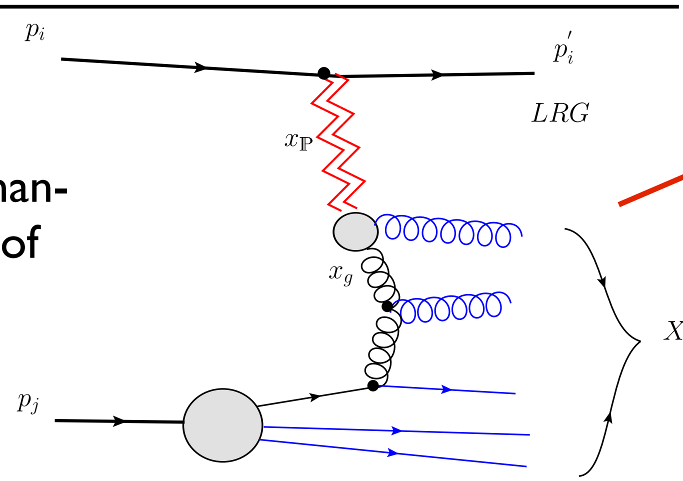
→ Typical string-fragmentation spectrum

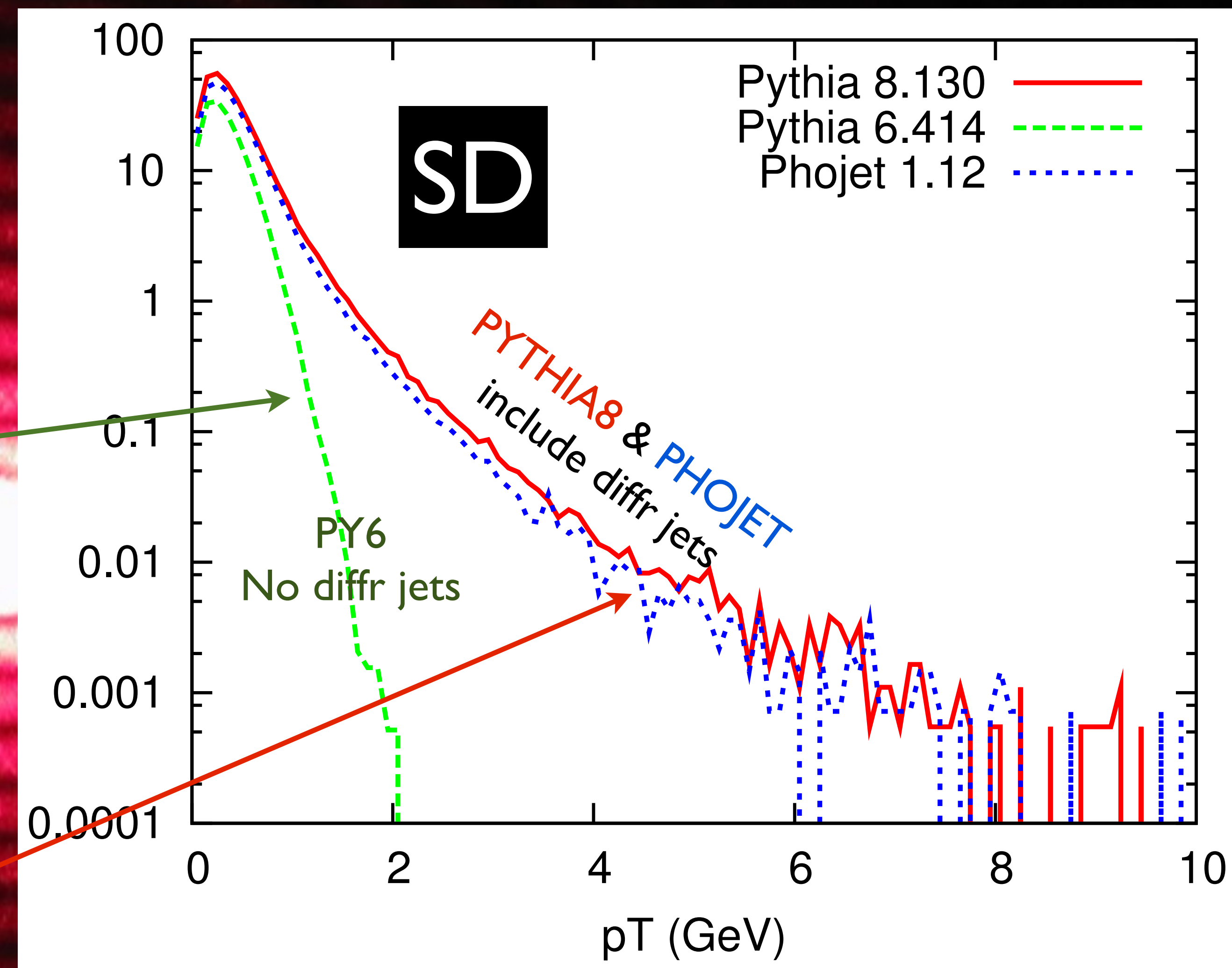
Partonic Substructure in Pomeron:

$M_X >$ 10 GeV

Follows the Ingelman-Schlein approach of Pompyt

PYTHIA 8





+ NEW! full MPI + showers for $\mathbb{P}$p system (→ UE in Diffraction)
+ NEW! Central Diffraction (→ fully contained gap-X-gap events)
+ NEW! Alternative Min-Bias Rockefeller (MBR) Model

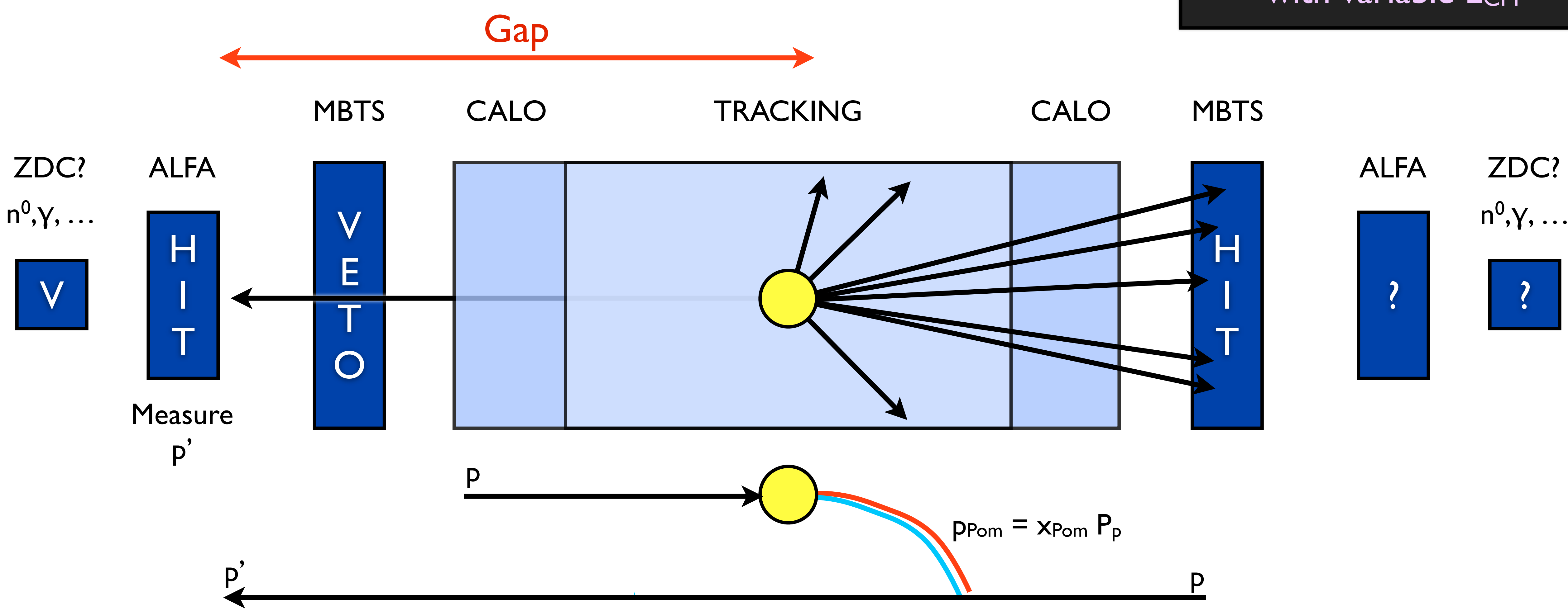
Choice between 5 Pomeron PDFs.
+ Recently Central Diffraction!

Free parameter $\sigma_{\mathbb{P}p}$ needed to fix $\langle n_{\text{interactions}}\rangle = \sigma_{\text{jet}}/\sigma_{\mathbb{P}p}$.
Framework needs testing and tuning, e.g. of $\sigma_{\mathbb{P}p}$.

(Some) Opportunities with ALFA + ATLAS

Single Diffraction

Glueball-Proton Collider with variable E_{CM}



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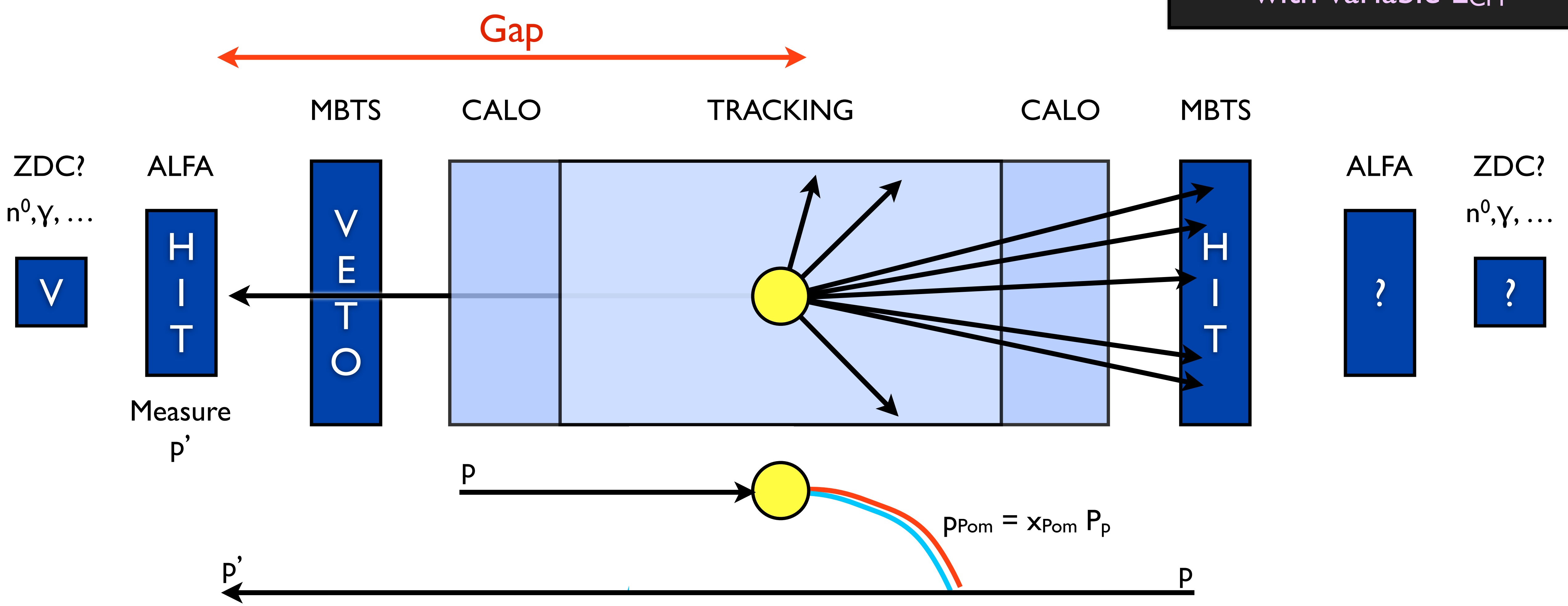

SD: Identified Particles

- Λ and K_S
- Other identified particles?
- Compare to minimum bias

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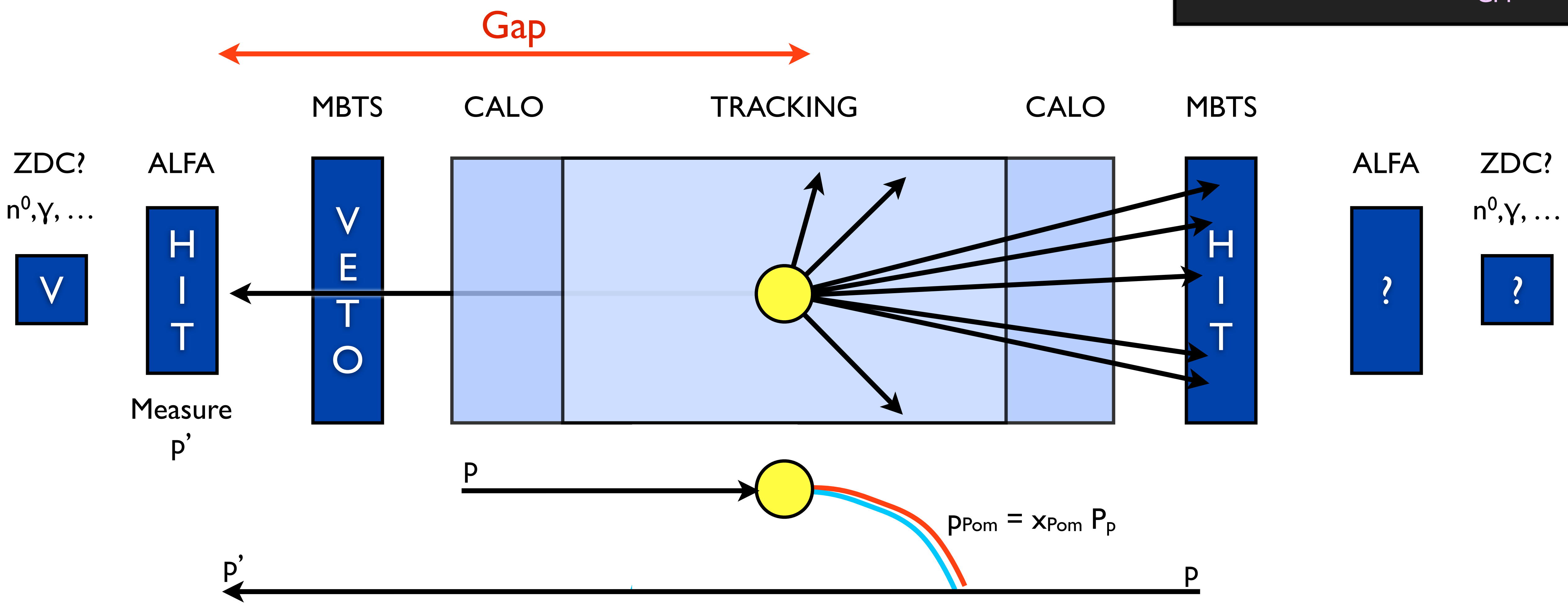

SD DIJETS

* Mass Spectrum (how high can you go?)
* Underlying Event in SD DIJET events
* Dijet Decorrelation $\Delta\varphi_{jj}$
* SD FOUR JETS (MPI in diffraction!)

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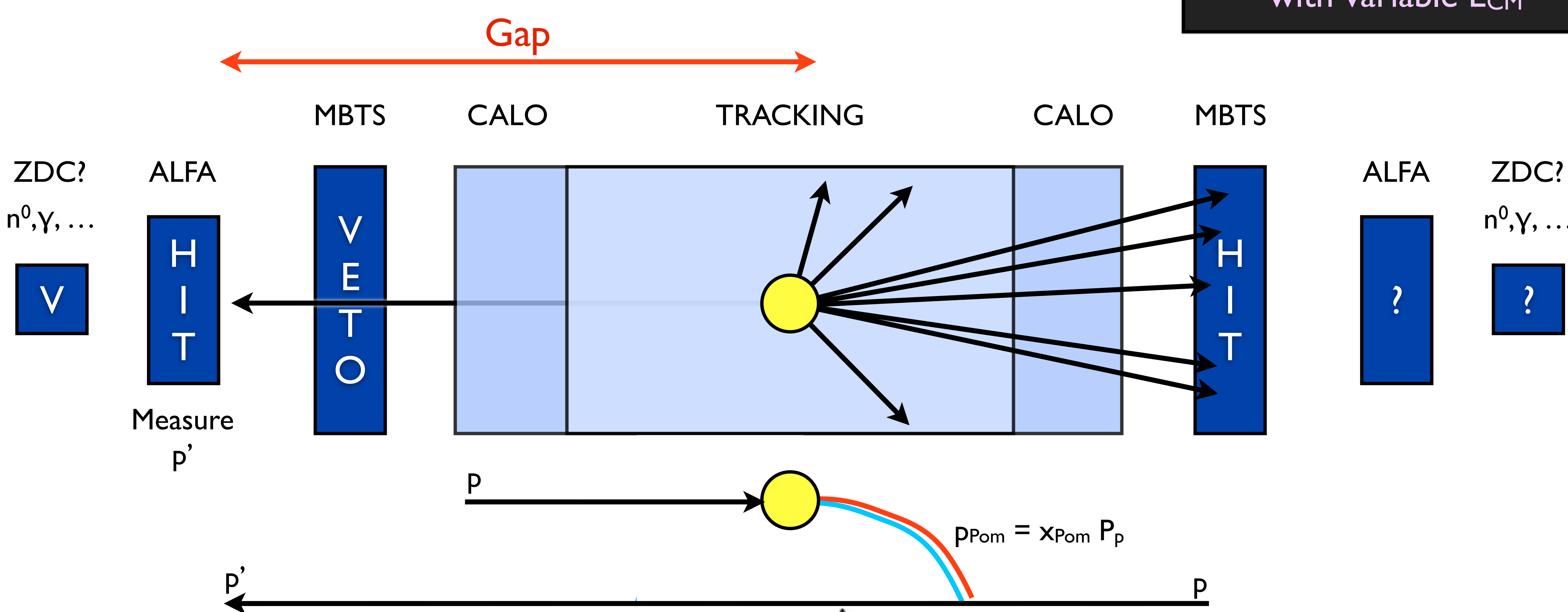

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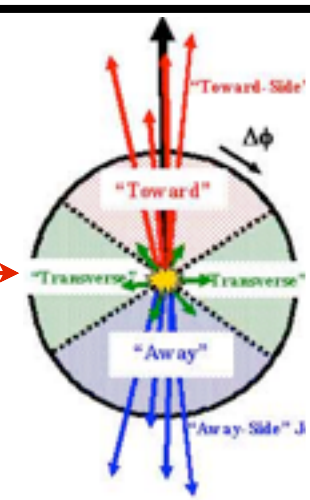

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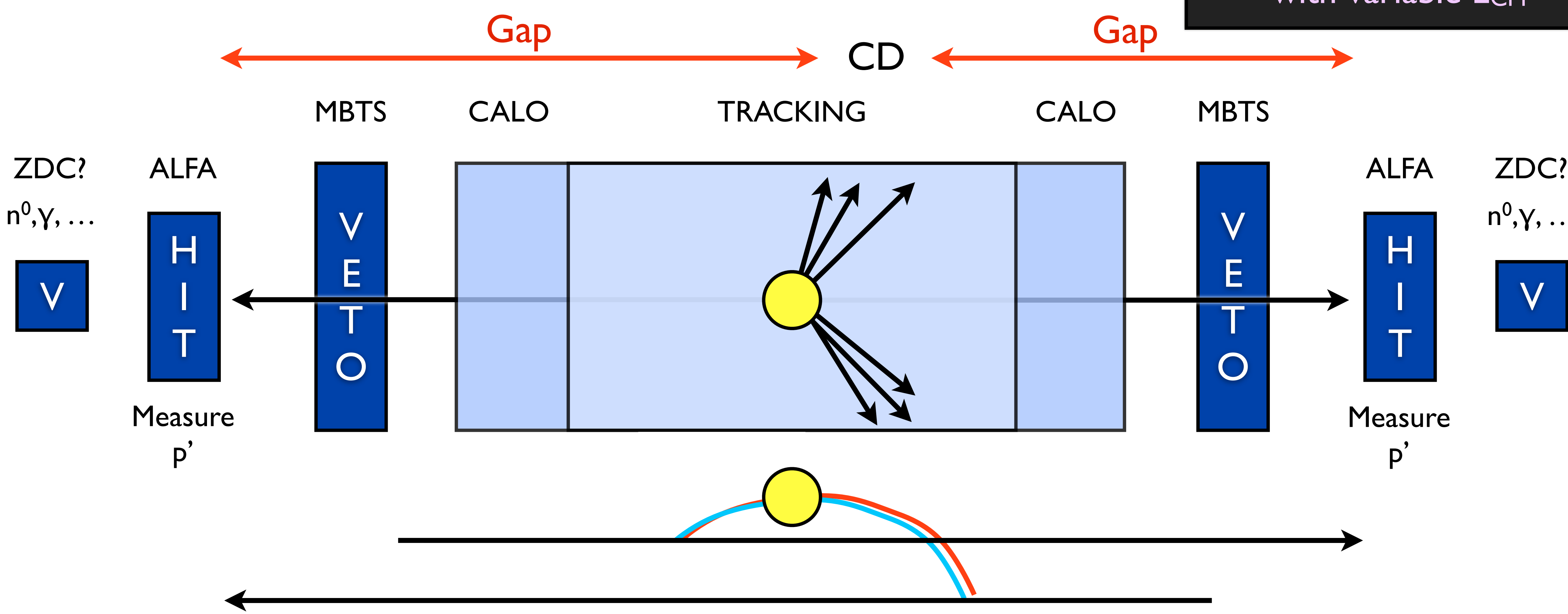
Central Diffraction

Glueball-Glueball Collider with variable E_{CM}



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Central Diffraction

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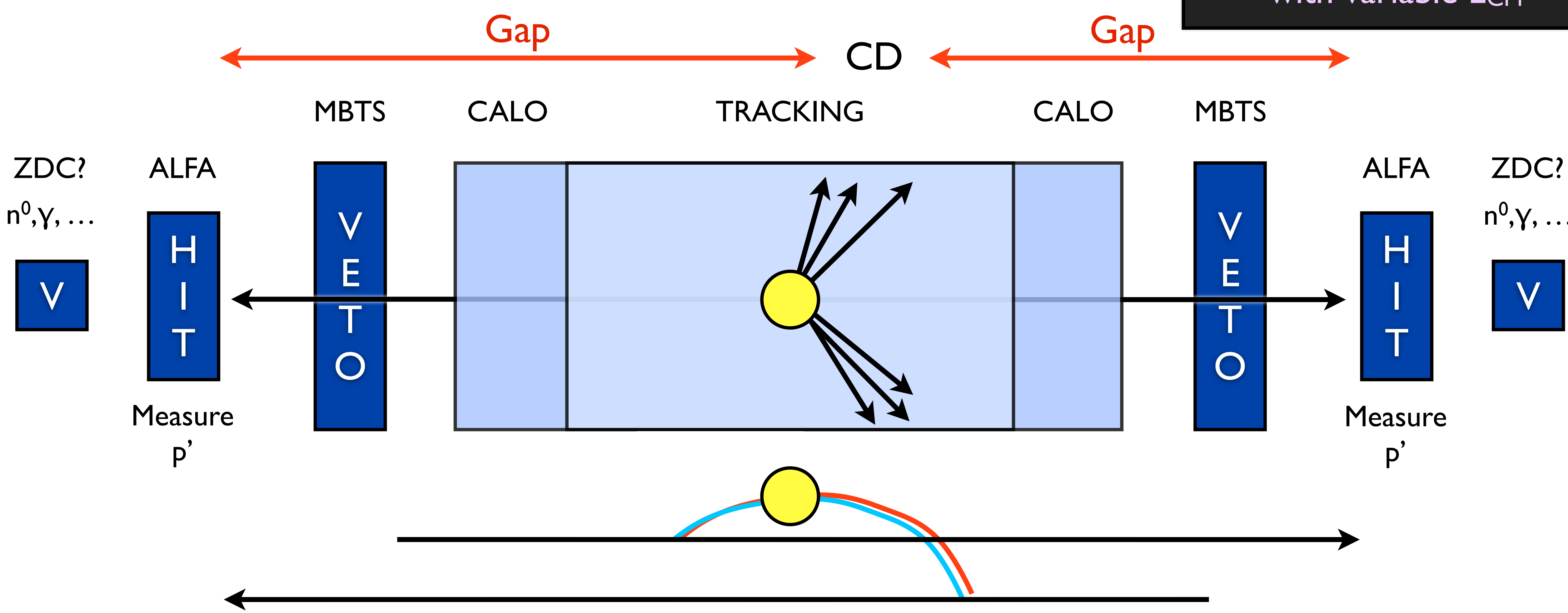


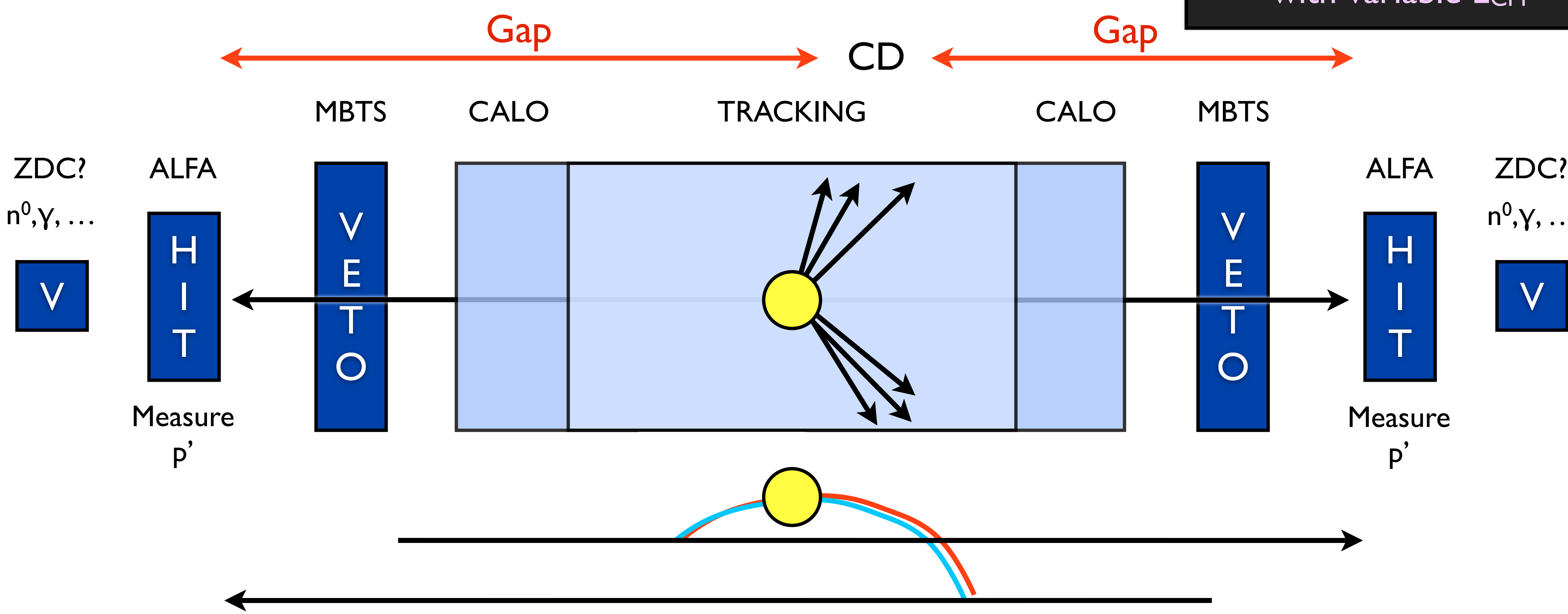
CD

* Mass Spectrum (how high can you go?)
* $\text{Mass}^2 = x_{\text{Pom}1}\, x_{\text{Pom}2}\, s$
* Rapidity of system $\rightarrow x_{\text{Pom}1} / x_{\text{Pom}2}$

(Some) Opportunities with ALFA + ATLAS

Central Diffraction

Glueball-Glueball Collider with variable E_{CM}



CD

* Mass Spectrum (how high can you go?)
* $\text{Mass}^2 = x_{\text{Pom}1}\, x_{\text{Pom}2}\, s$
* Rapidity of system → $x_{\text{Pom}1} / x_{\text{Pom}2}$

CD JETS

* Underlying Event
* Dijet Decorrelation, $\Delta\varphi_{jj}$

(Some) Opportunities with ALFA + ATLAS

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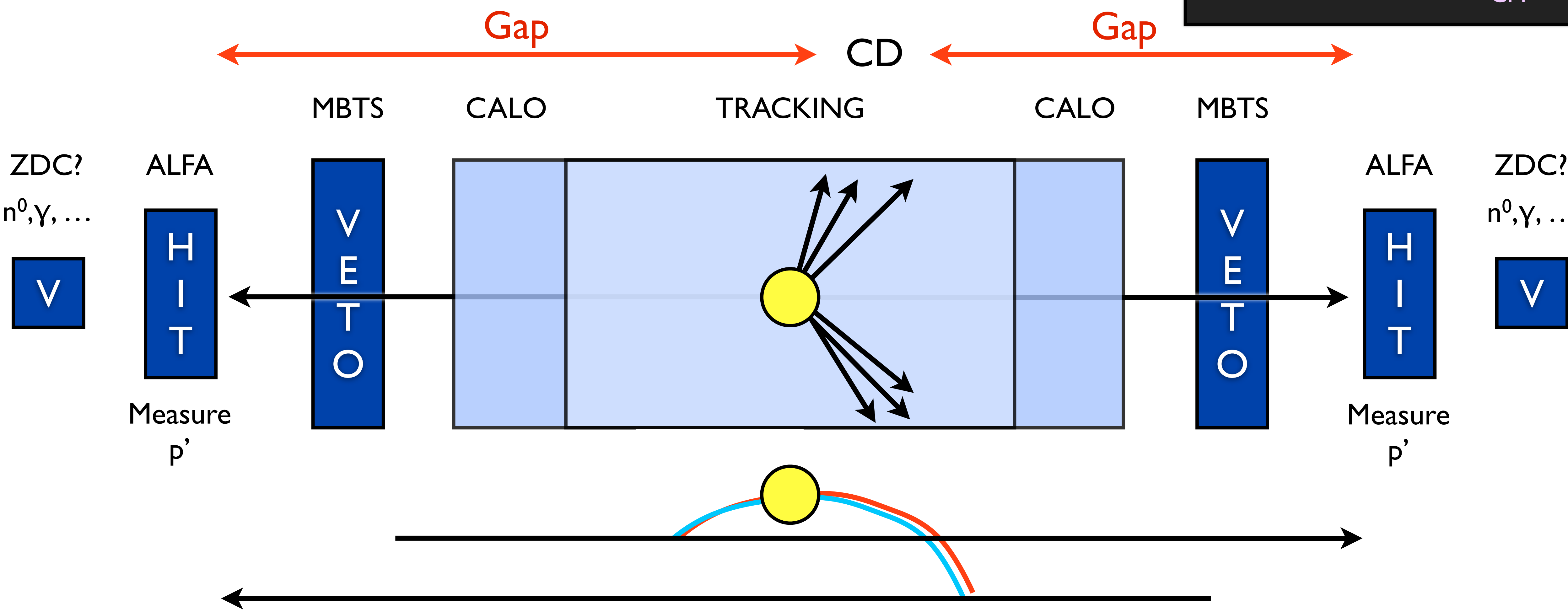

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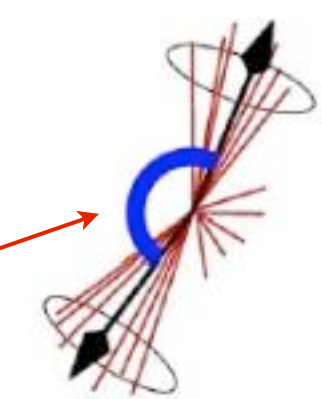

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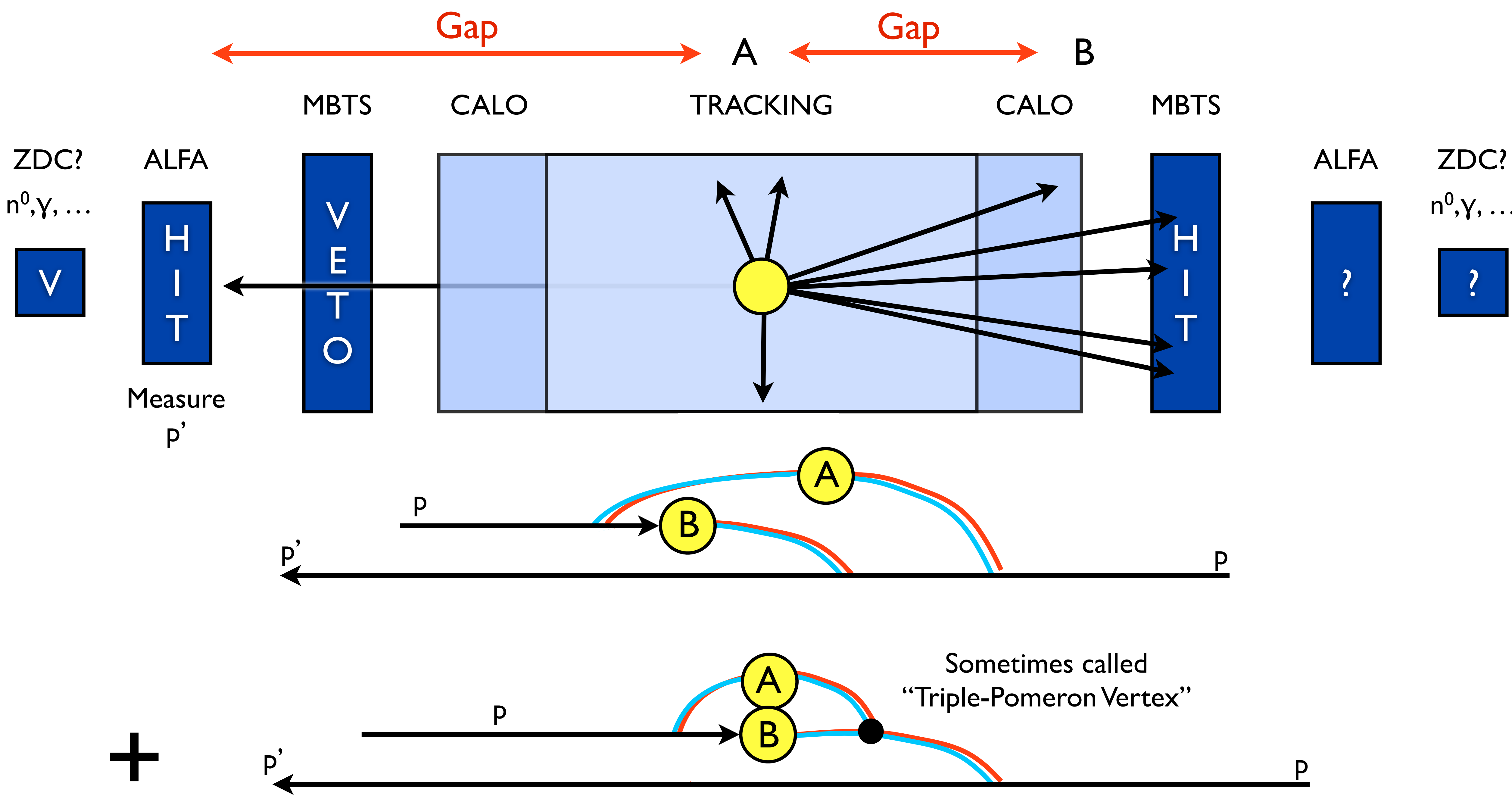
Multi-Gap Diffraction (= Subset of Single-Gap)



Wait … is this Crazy?

Best tuning result (and default in PYTHIA)

Obtained with $\alpha_s(M_Z) \approx 0.14$

$\neq$ World Average $= 0.1176 \pm 0.0020$

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MC ≈ Leading Order + LL resummation

Other LO extractions of $\alpha_s \approx 0.13 - 0.14$

Effective scheme interpreted as "CMW" → 0.13;

2-loop running → 0.127; NLO → 0.12 ?

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Tune/measure even pQCD parameters with the actual generator.

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Improve → Matching at LO and NLO