Experimental Methods and Physics at the LHC

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24th Vietnam School of Physics: Particles and Cosmology

Jets and Jet-related Measurements

Useful Links and Disclaimer

- Jet lectures by Gavin Salam
  - https://gsalam.web.cern.ch/gsalam/teaching/PhD-courses.html
- A lot of the material/ideas in this lecture are borrowed from his slides

Definition of Jets

What Is a Jet?

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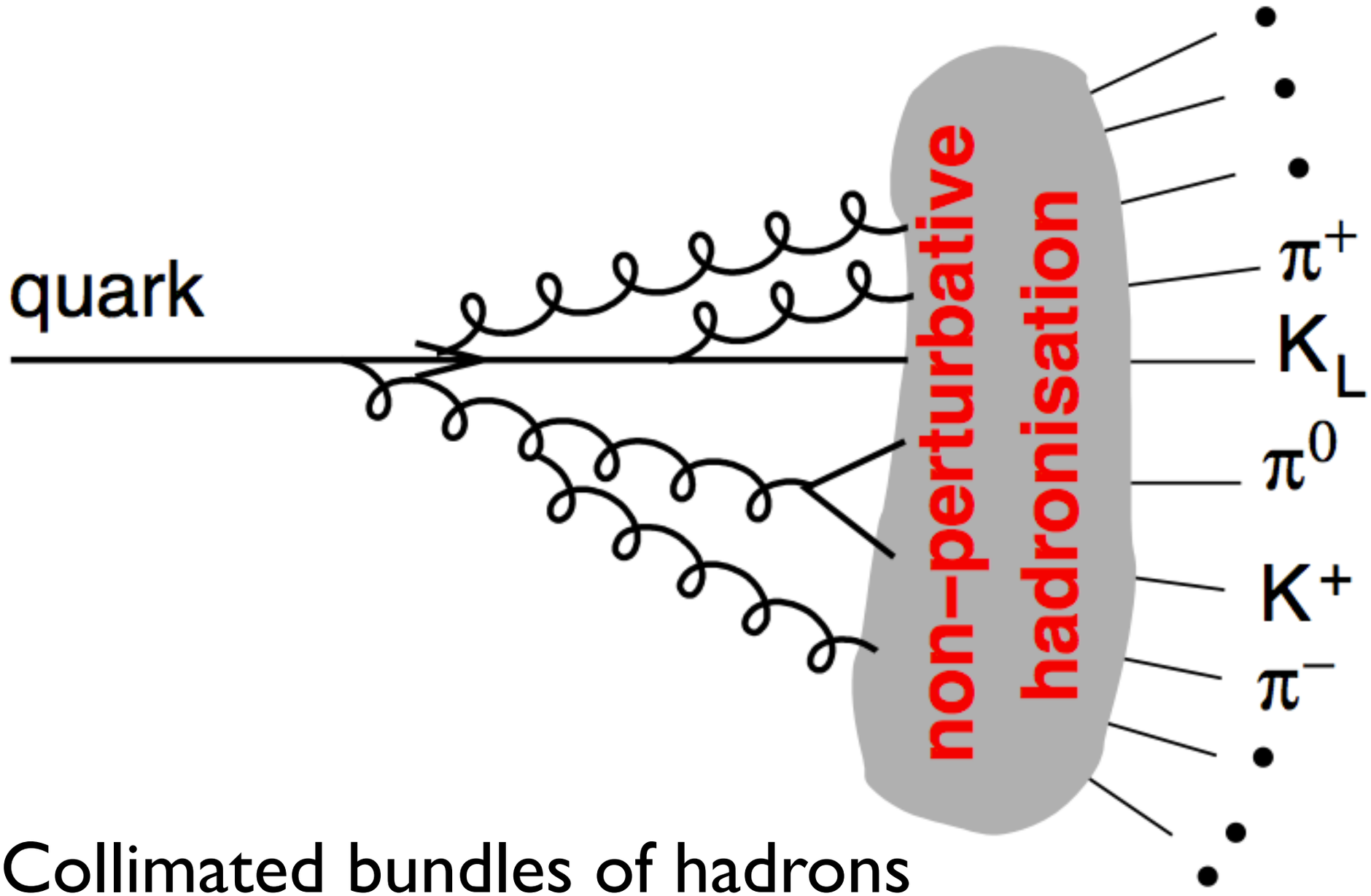
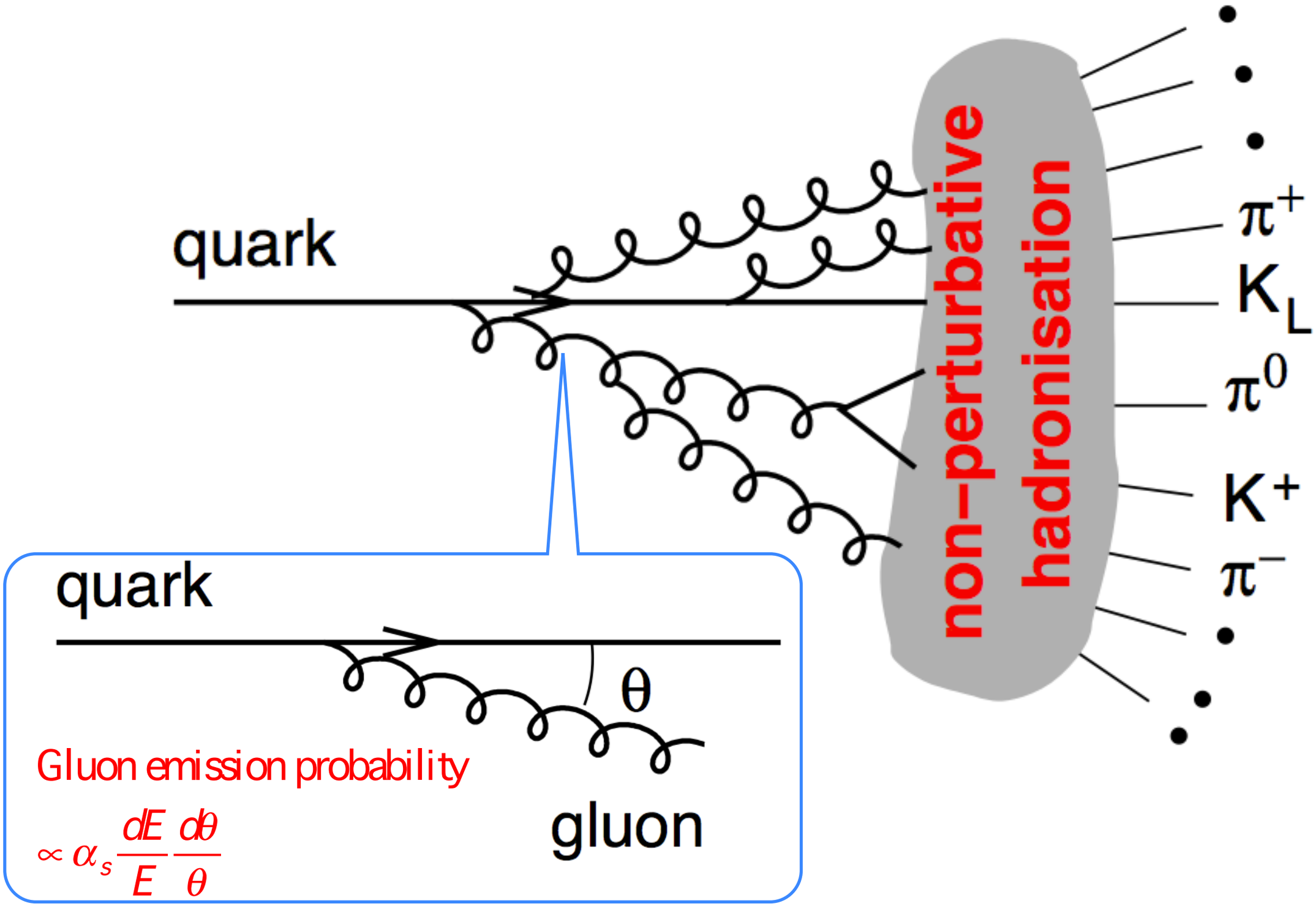


- Collimated bundles of hadrons
  - quarks or gluons that undergo soft and collinear showering, and then hadronization

What Is a Jet?


quark
non-perturbative
hadronisation
π^+
K_L
π^0
K^+
π^-
quark
θ
Gluon emission probability
$\propto \alpha_s \frac{dE}{E} \frac{d\theta}{\theta}$
gluon

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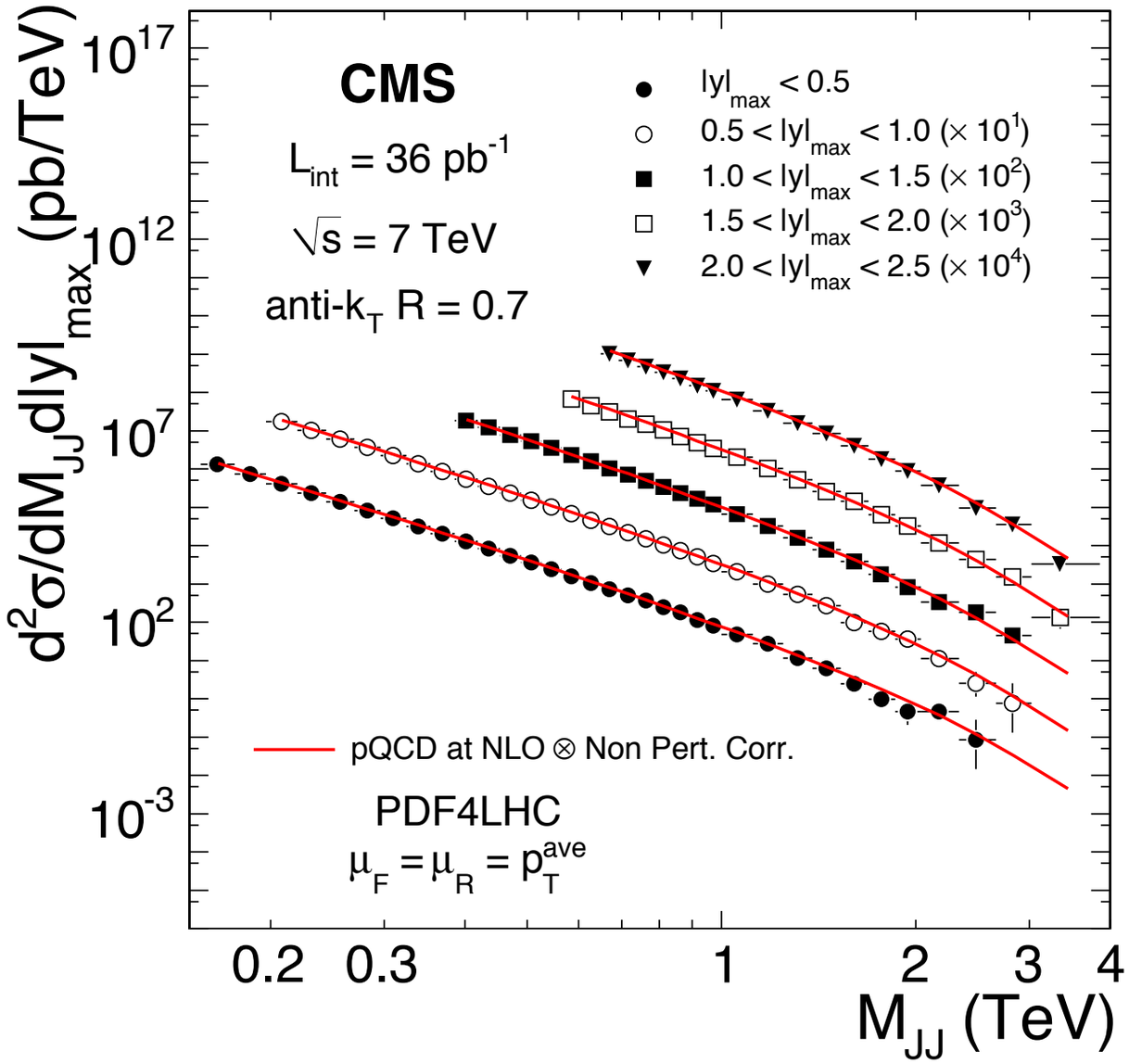
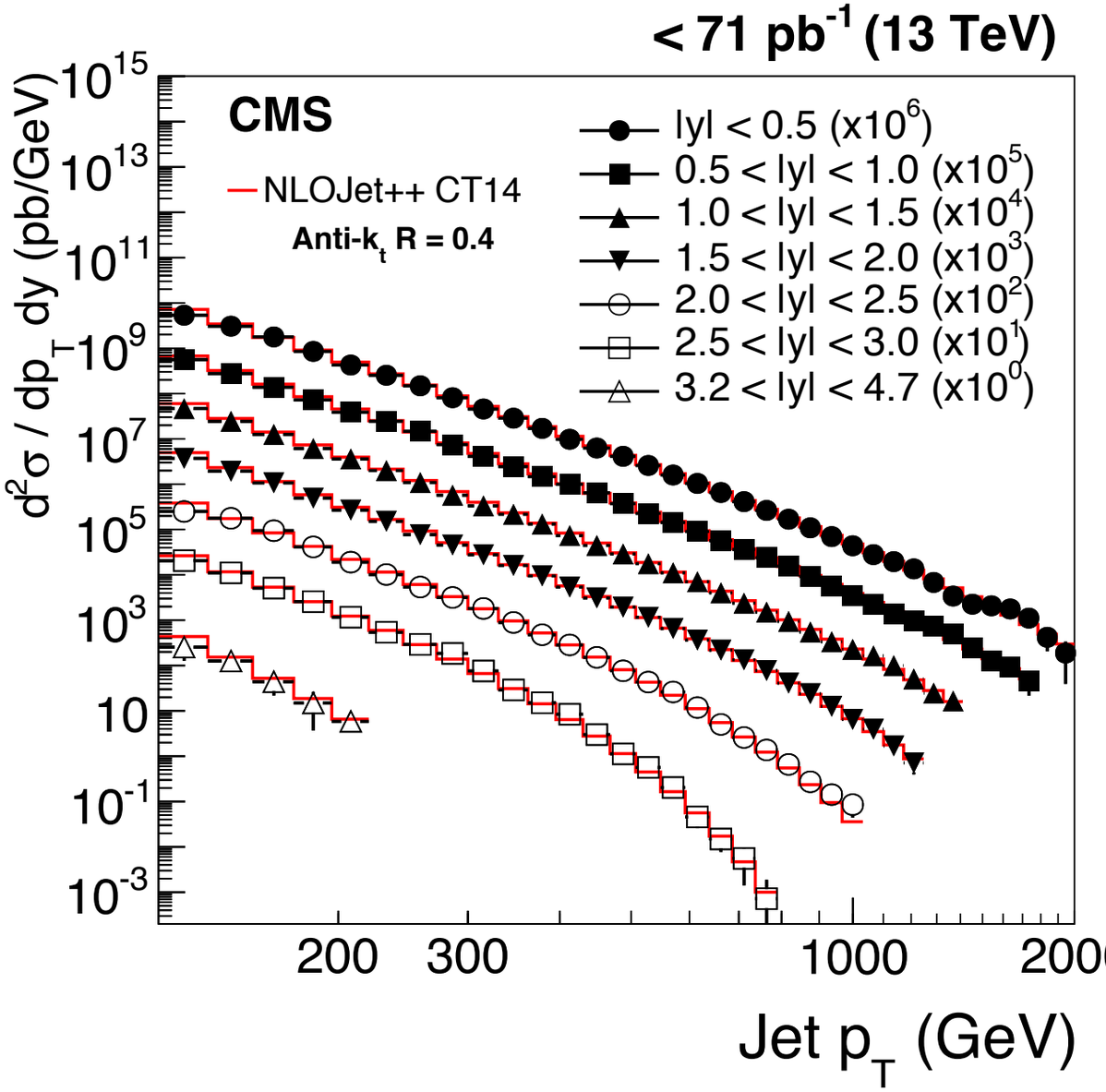
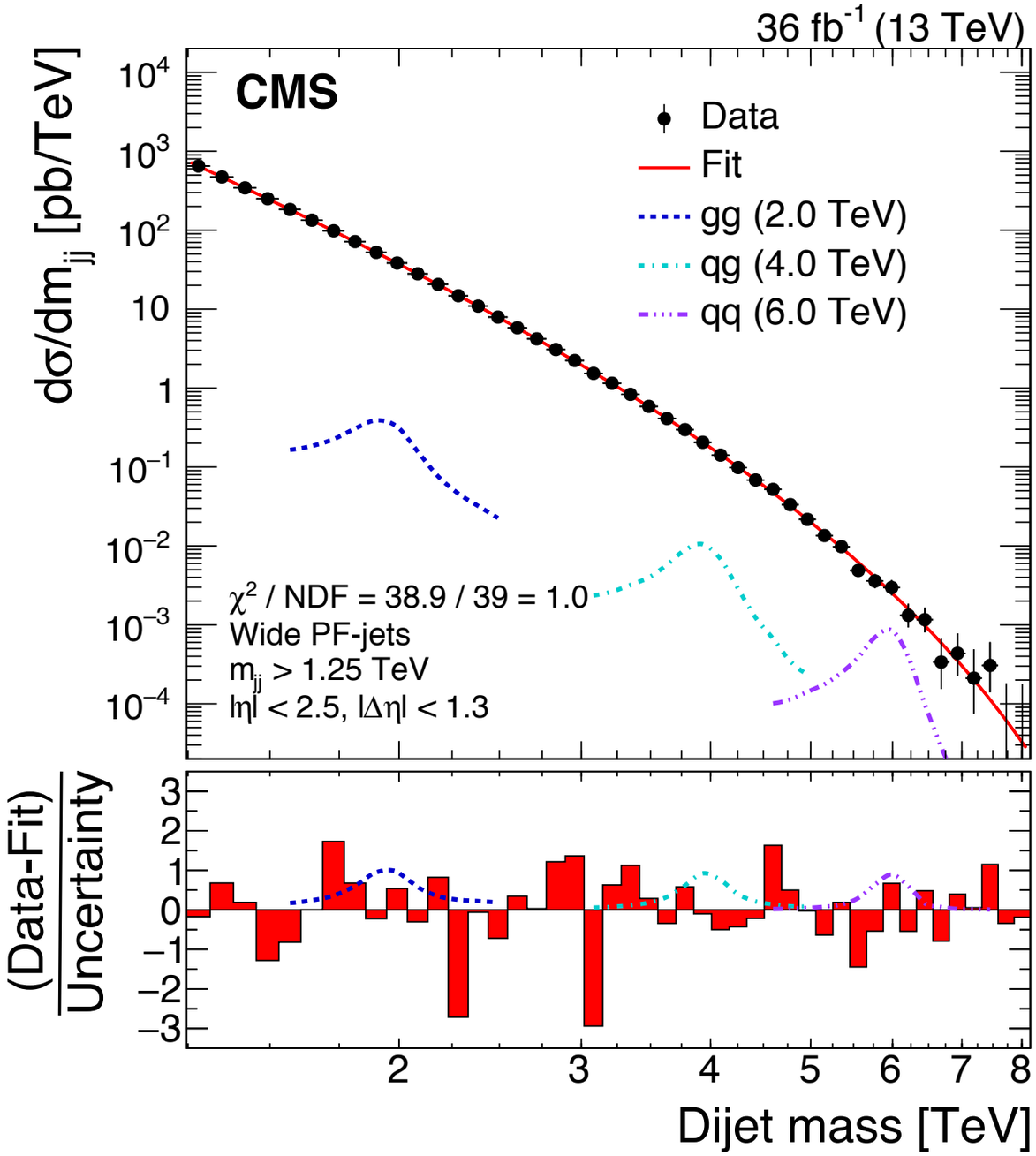
  - Dijet resonance search
  - W-jet, Z-jet, Higgs-jet

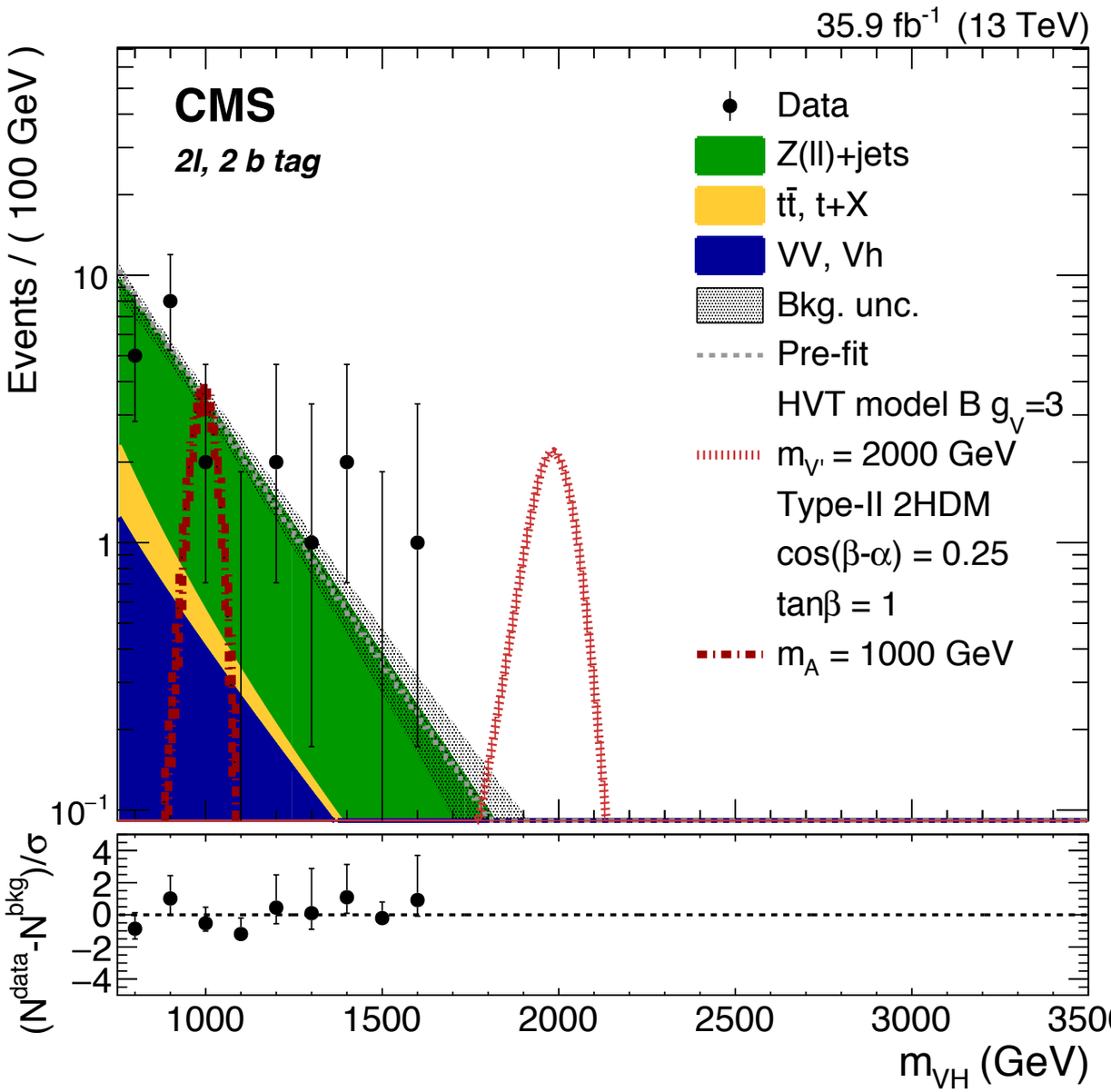
LHC Jet Cross Section





LHC Jet-related Searches





An Event Display with Jets

by G. Salam

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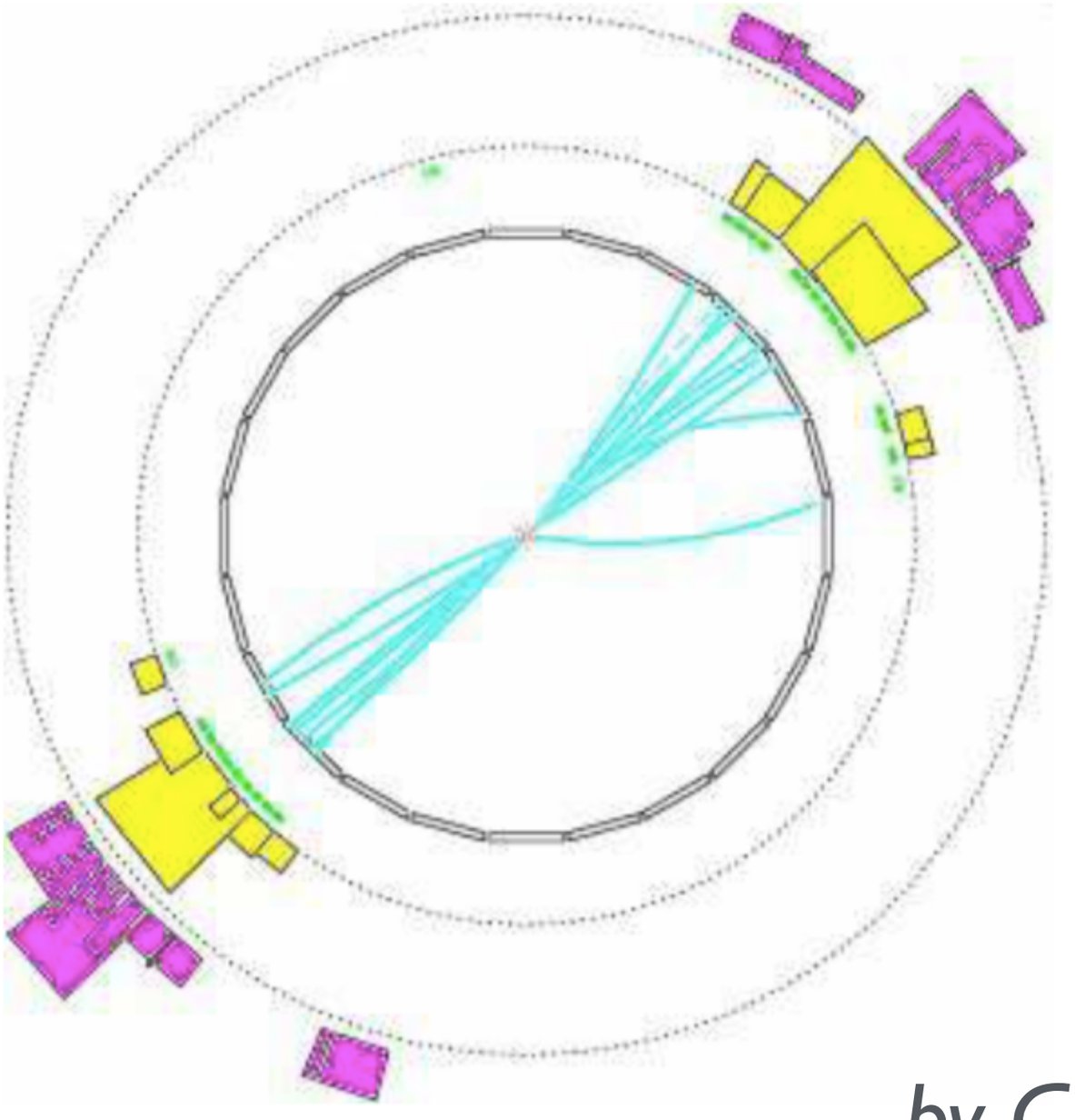

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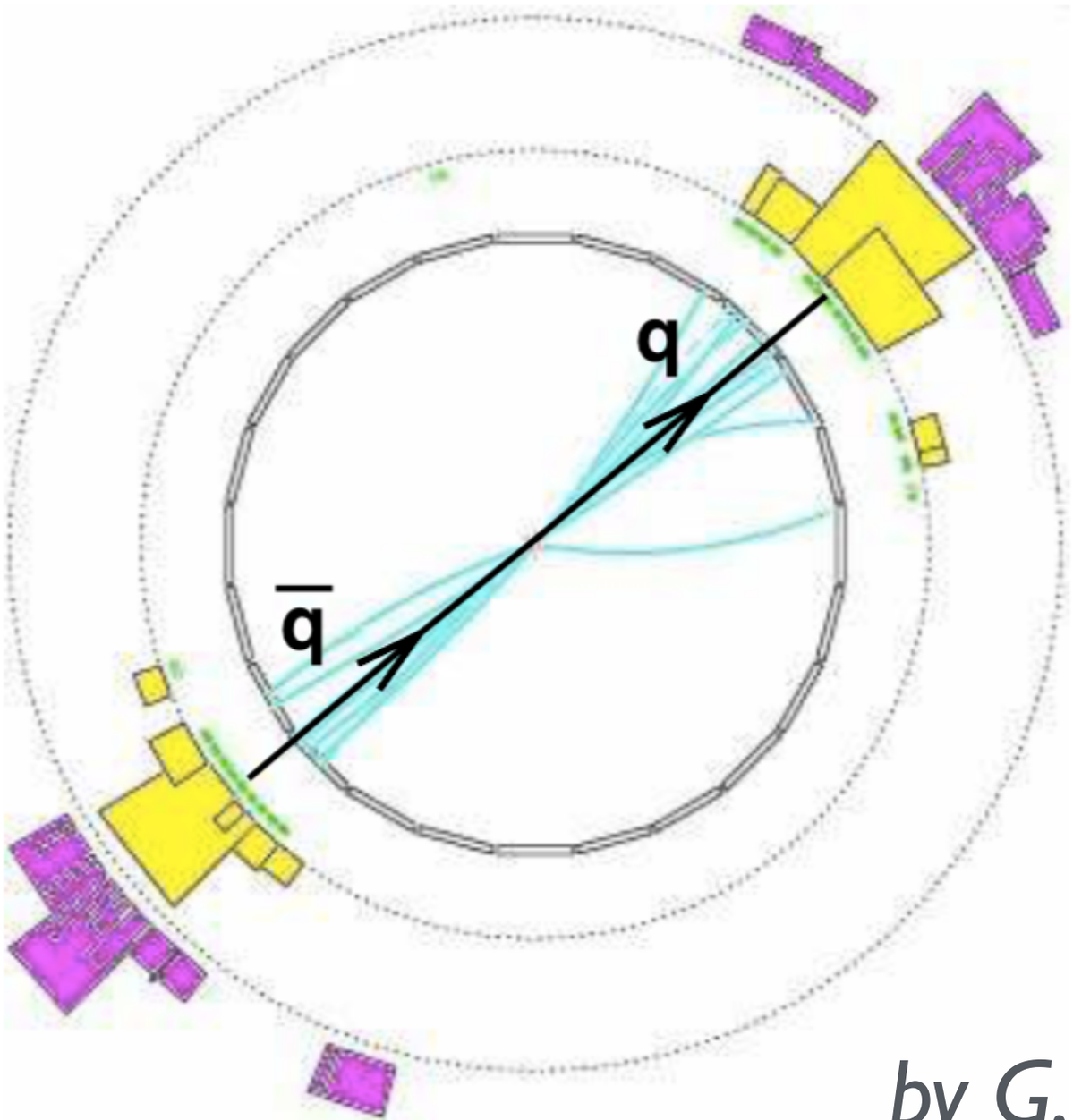
clearly a two-jet event



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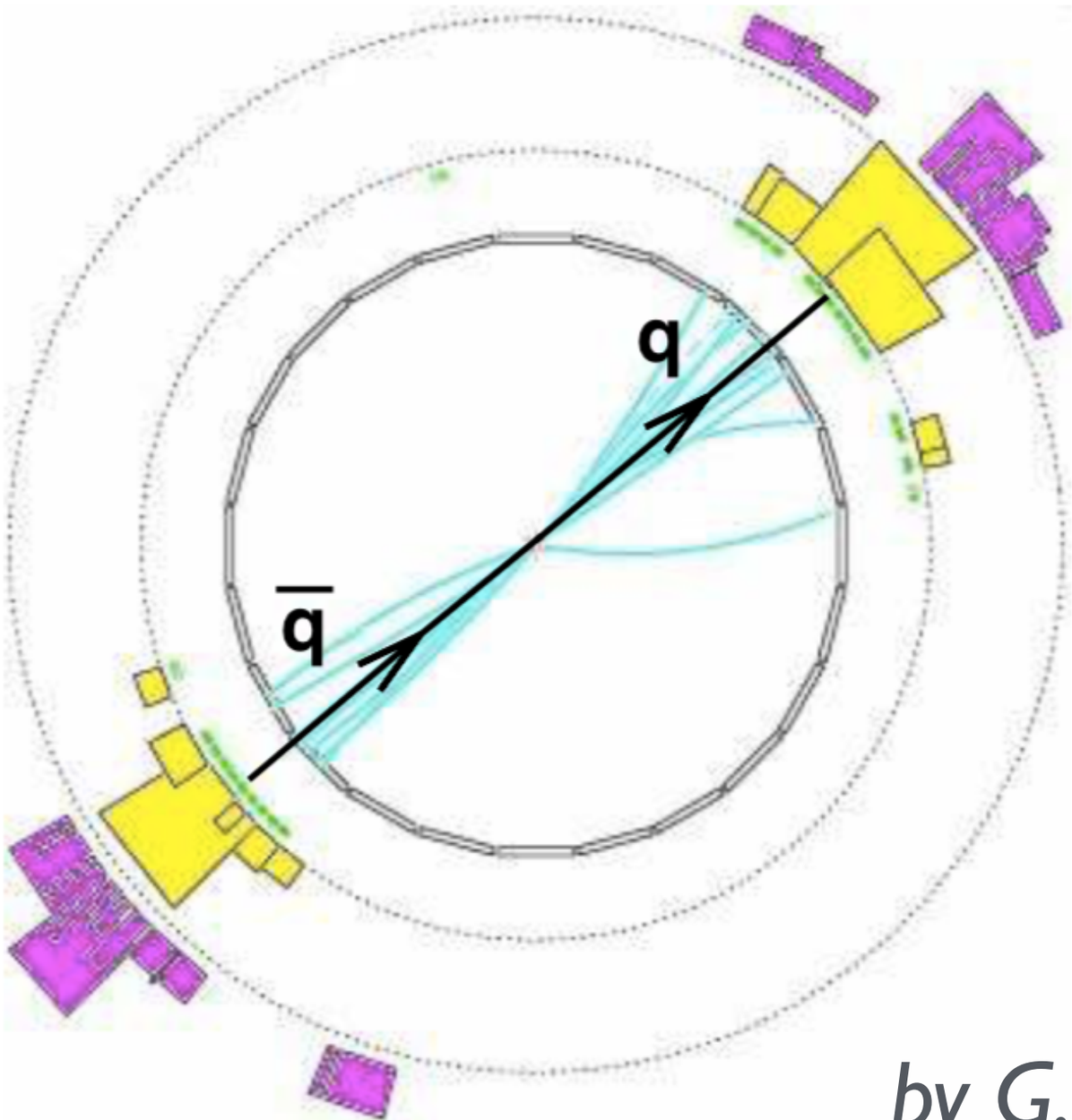

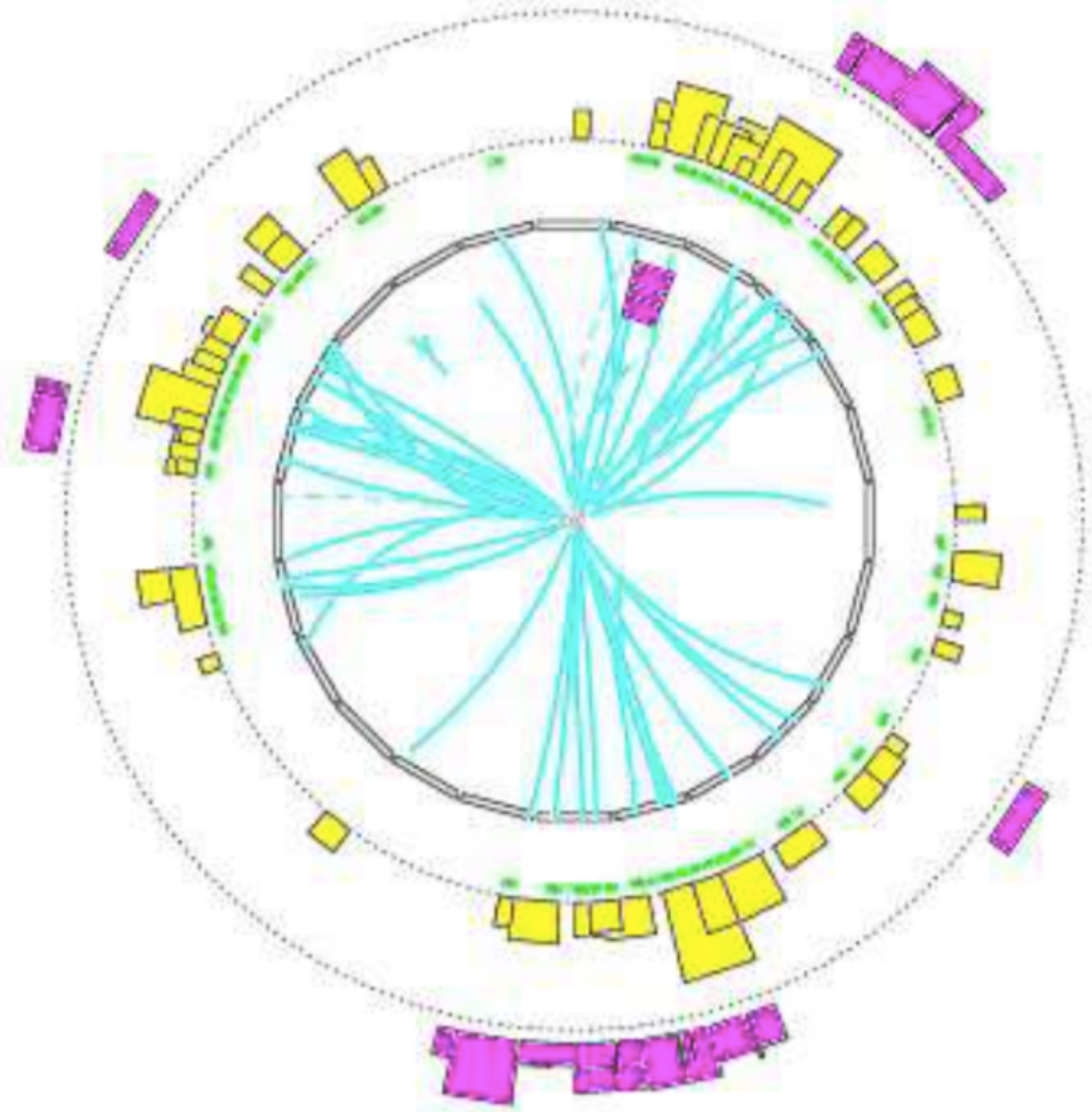

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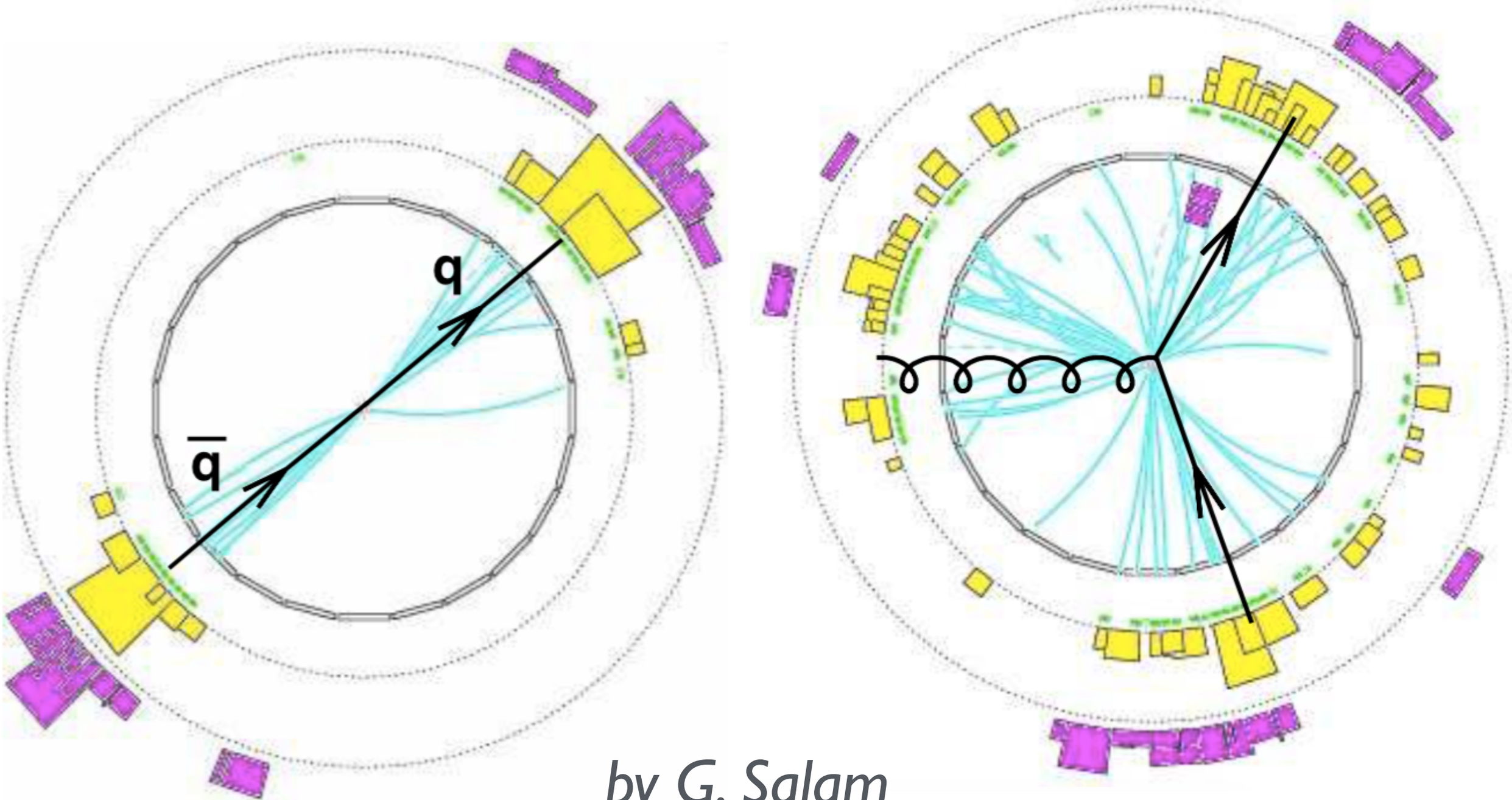

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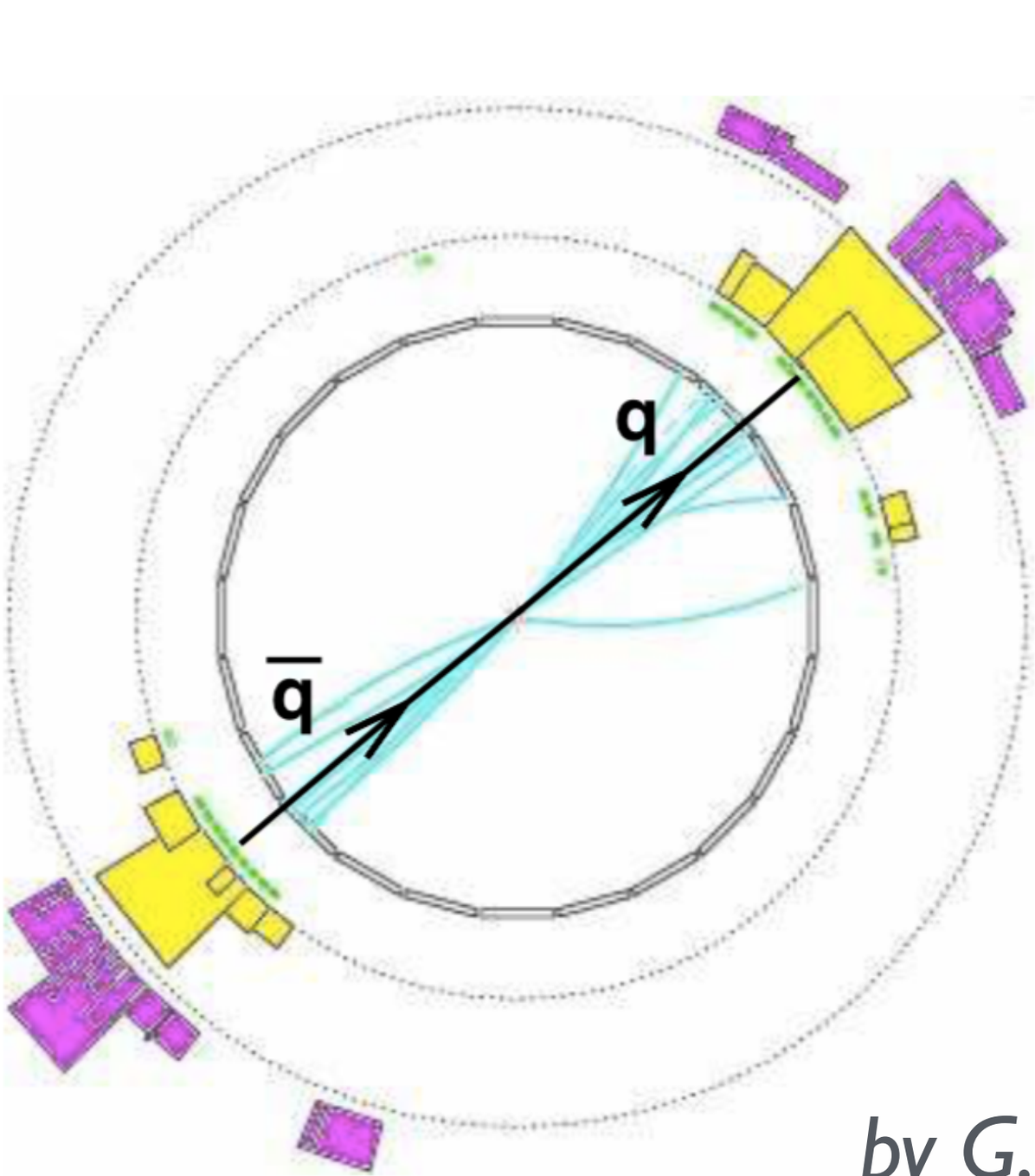

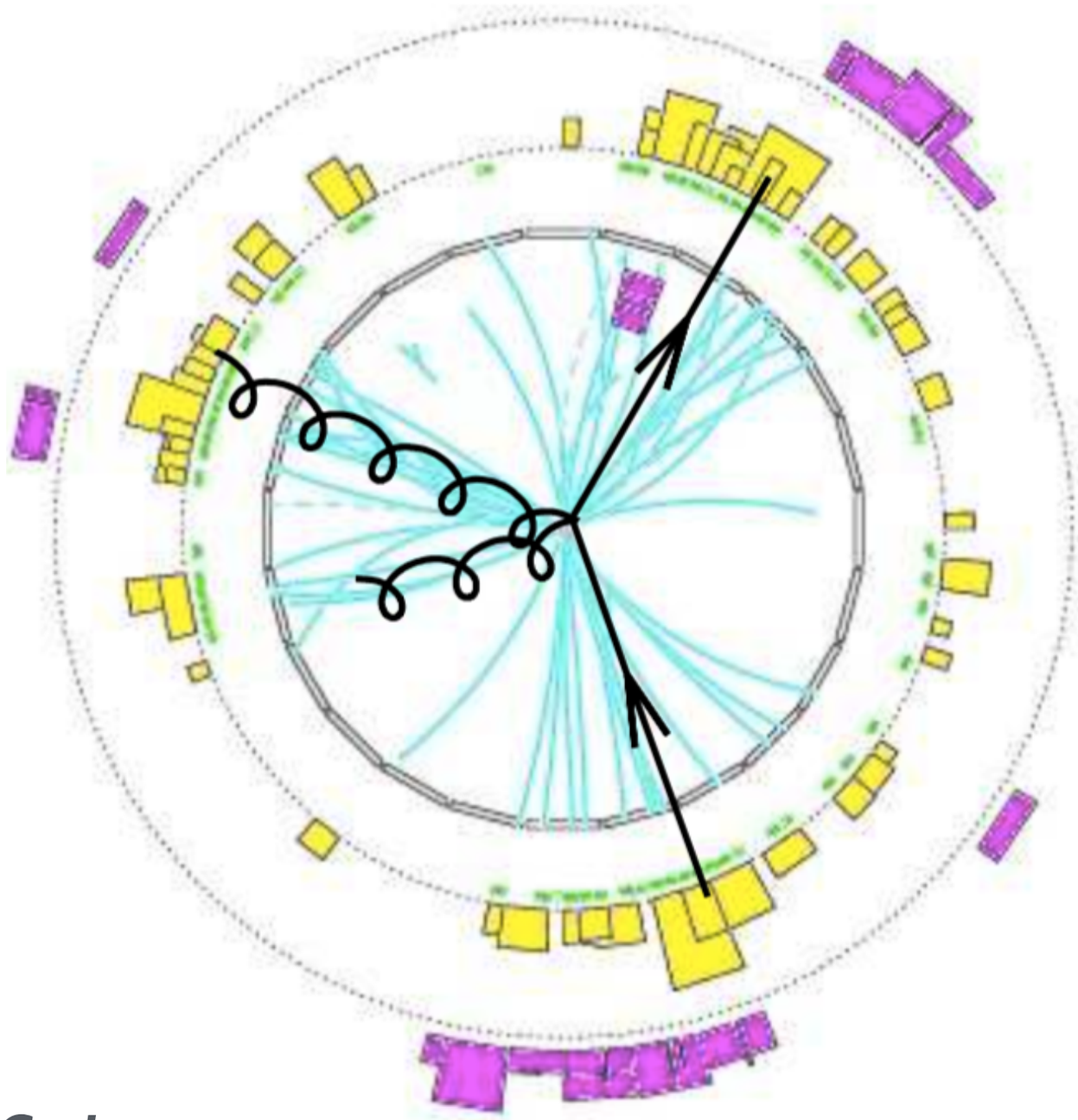

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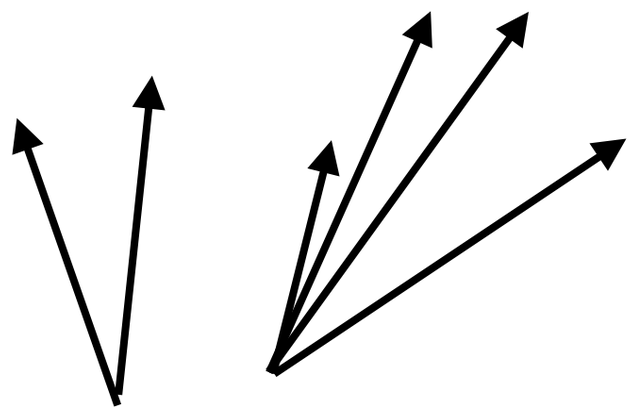
- Must be collinear and infrared safe
  - collinear: angle between emitting gluons and original parton is much smaller than 1
  - infrared: ratio of gluon to parton energy is much smaller than 1

Combination of Particles into One Jet

- How do we decide if two particles should be combined and clustered into one jet?



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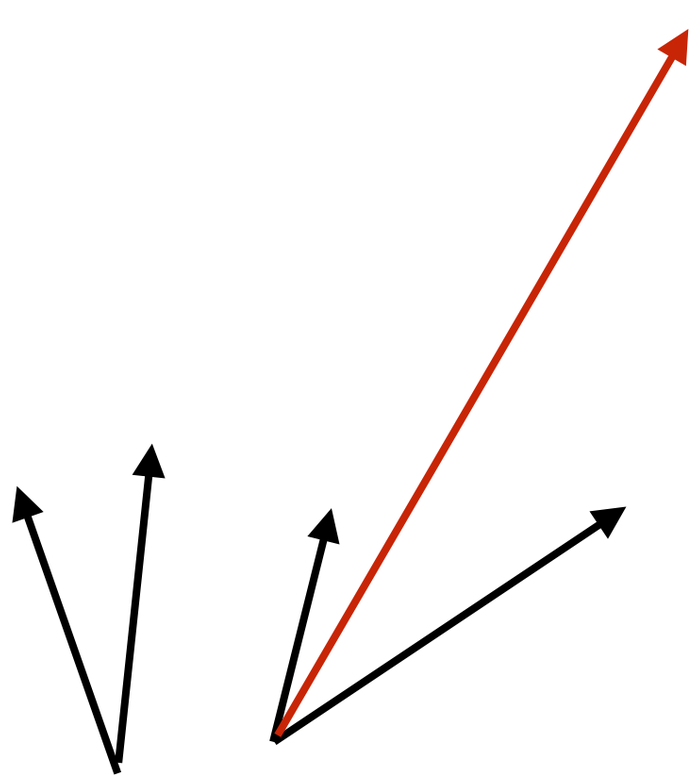

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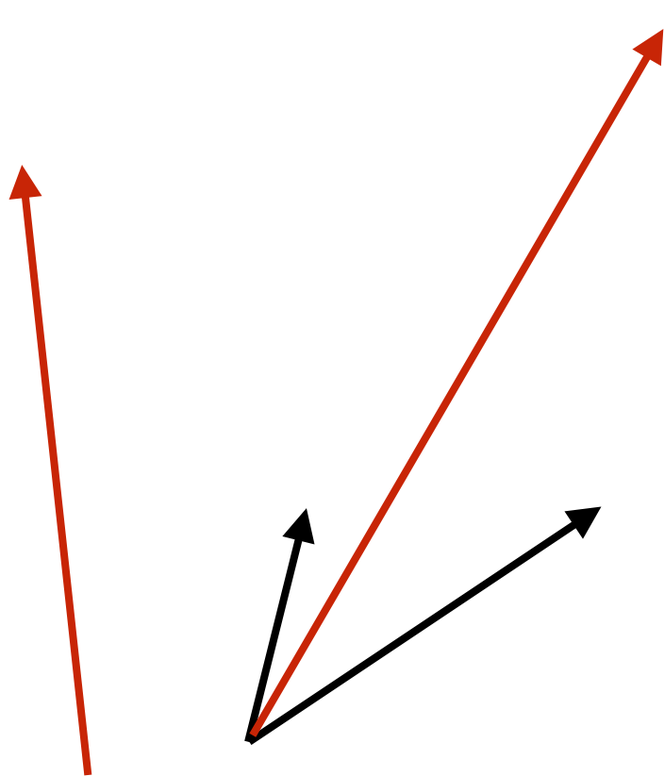
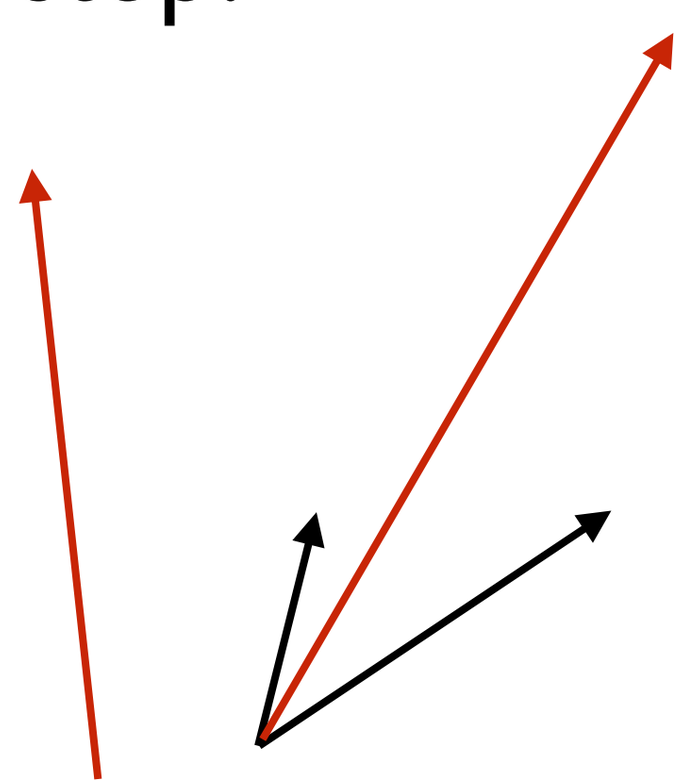


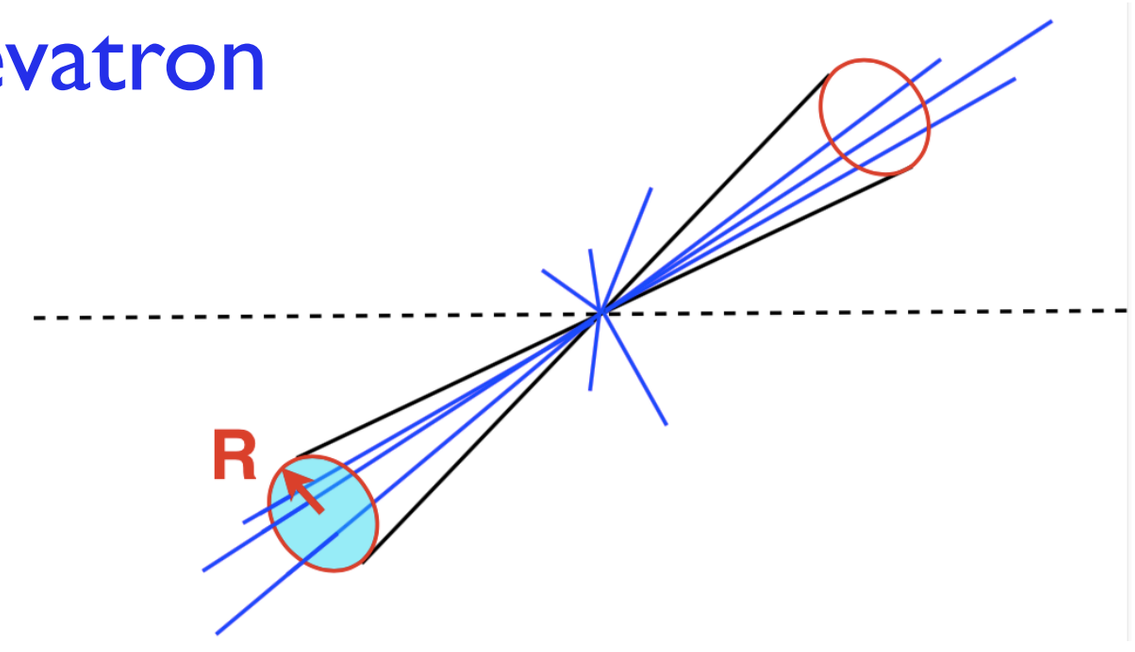
Combination of Particles into One Jet

- How do we decide if two particles should be combined and clustered into one jet?
- When do we stop?



Jet Algorithms

- Sequential recombination
  - most widely used at LHC and HERA
  - successively undoes QCD branching
- Cone
  - most widely used at Tevatron
  - directed energy flow



k_t Algorithm in e^+e^- Machines

- QCD branching probability grows with decreasing gluon energy and decreasing angle between emitted gluon and mother parton
- In e^+e^- machines, the k_t algorithm is defined as:

k_t Algorithm in e^+e^- Machines

1. Calculate (or update) distances between all particles i and j:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

NB: relative k_t between particles

2. Find smallest of y_{ij}
   - If $> y_{cut}$, stop clustering
   - Otherwise recombine i and j, and repeat from step 1

Catani, Dokshitzer, Olsson, Turnock & Webber '91

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single parameter

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k_t Algorithm in Hadron Colliders

- Introduce angular radius R (NB: dimensionless!)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}\,, \qquad d_{iB} = p_{ti}^2$$

- 1. Find smallest of d_{ij}, d_{iB}
  2. if ij, recombine them
  3. if iB, call i a jet and remove from list of particles
  4. repeat from step 1 until no particles left.

S.D. Ellis & Soper, '93; the simplest to use

Jets all separated by at least R on y, ϕ cylinder.

NB: number of jets not IR safe (soft jets near beam); number of jets above p_t cut **is** IR safe.

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two parameters

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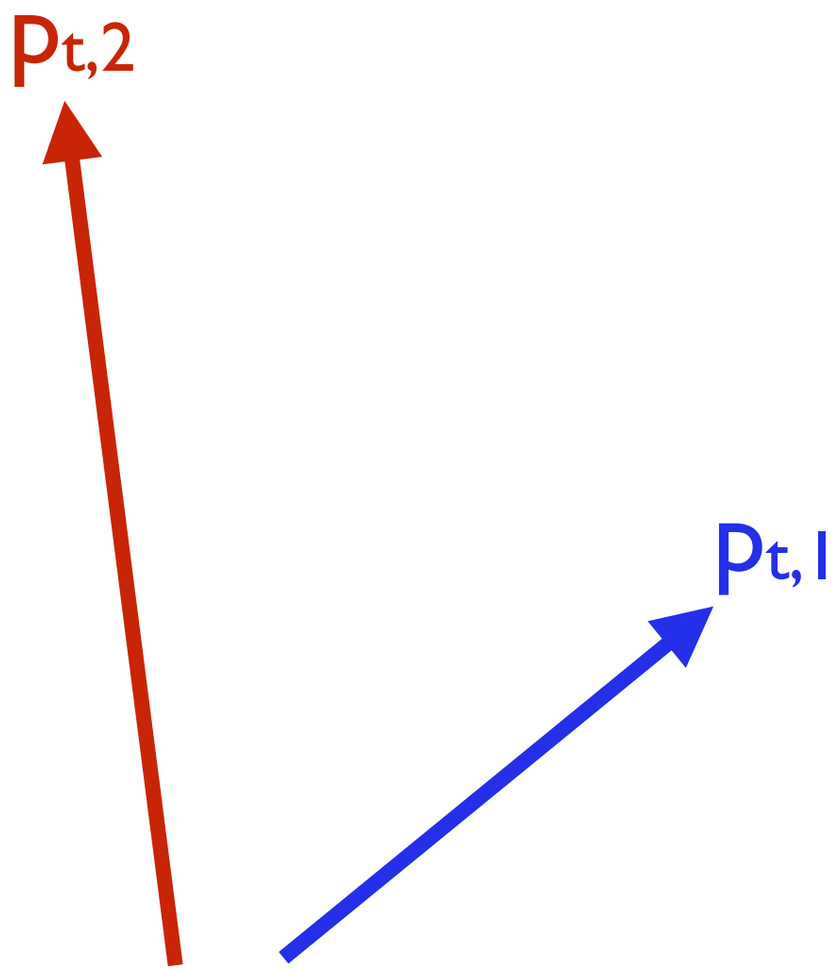
Example: Should We Combine These Two Particles?



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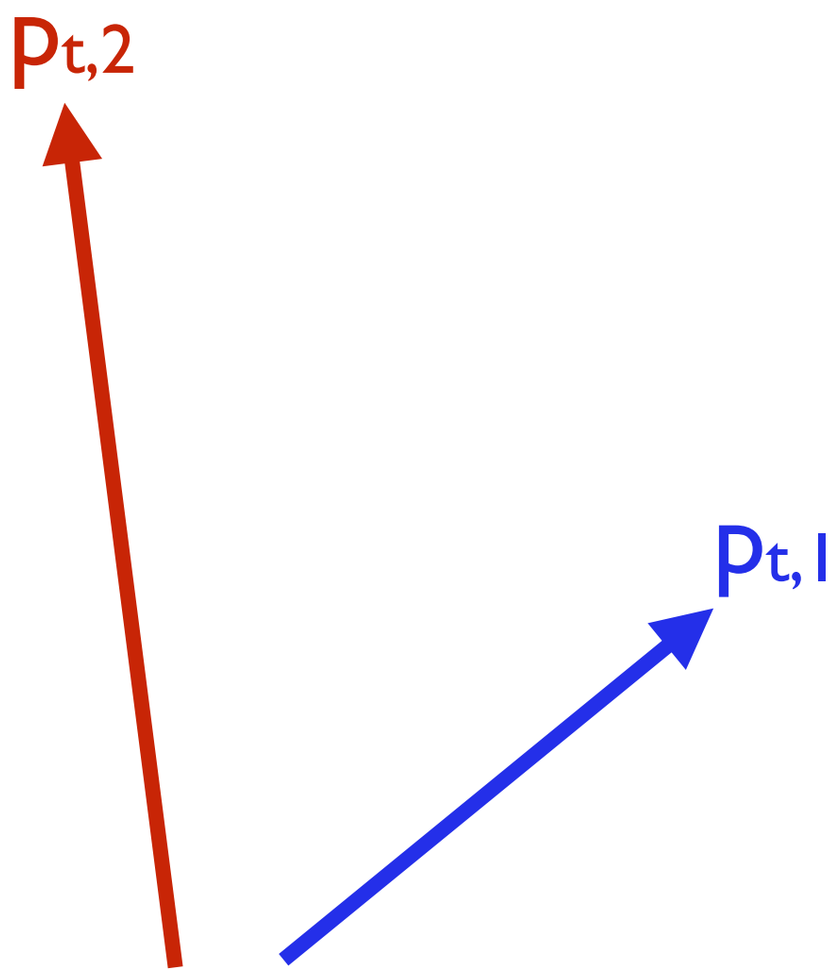

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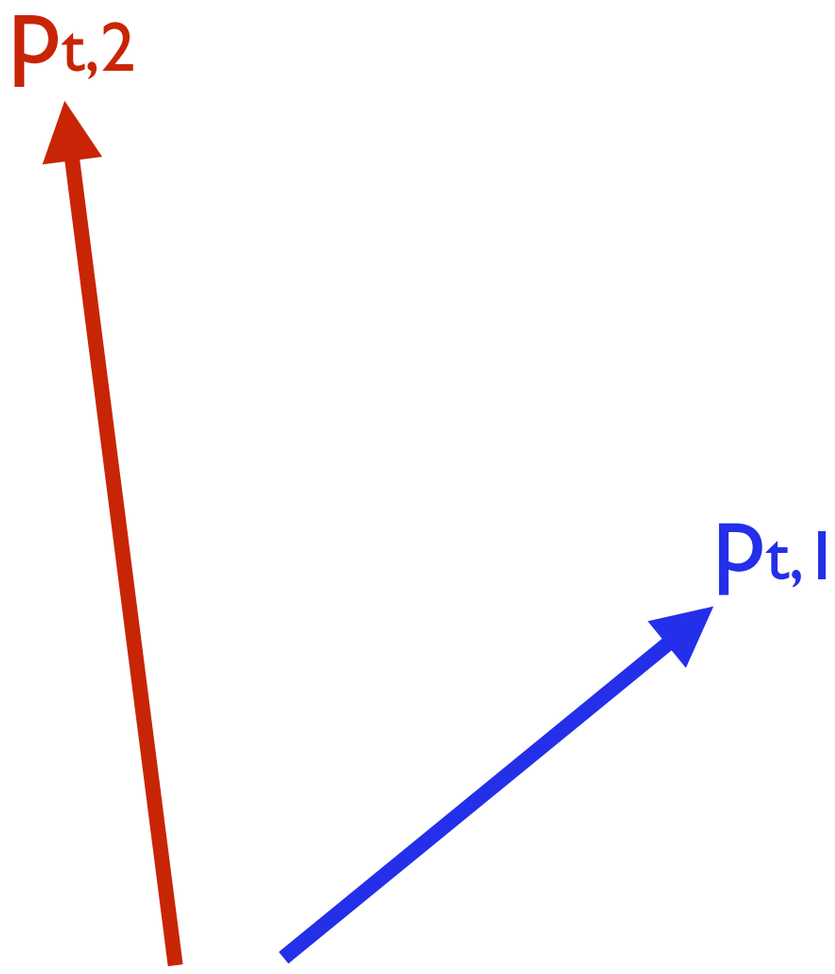

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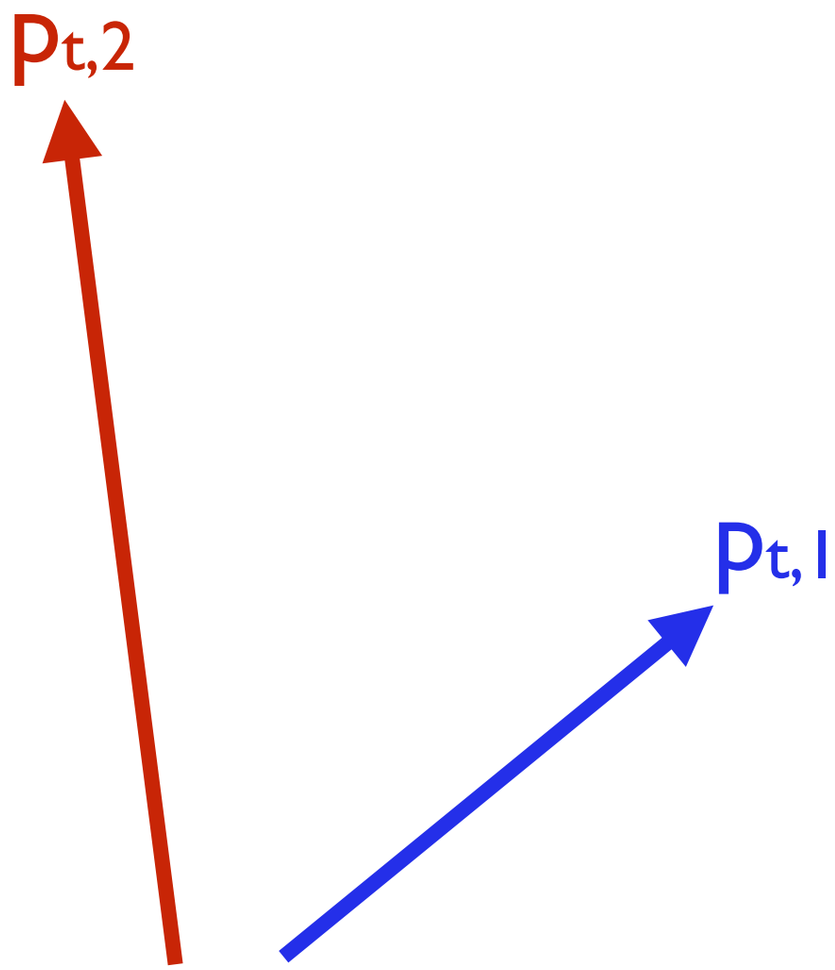

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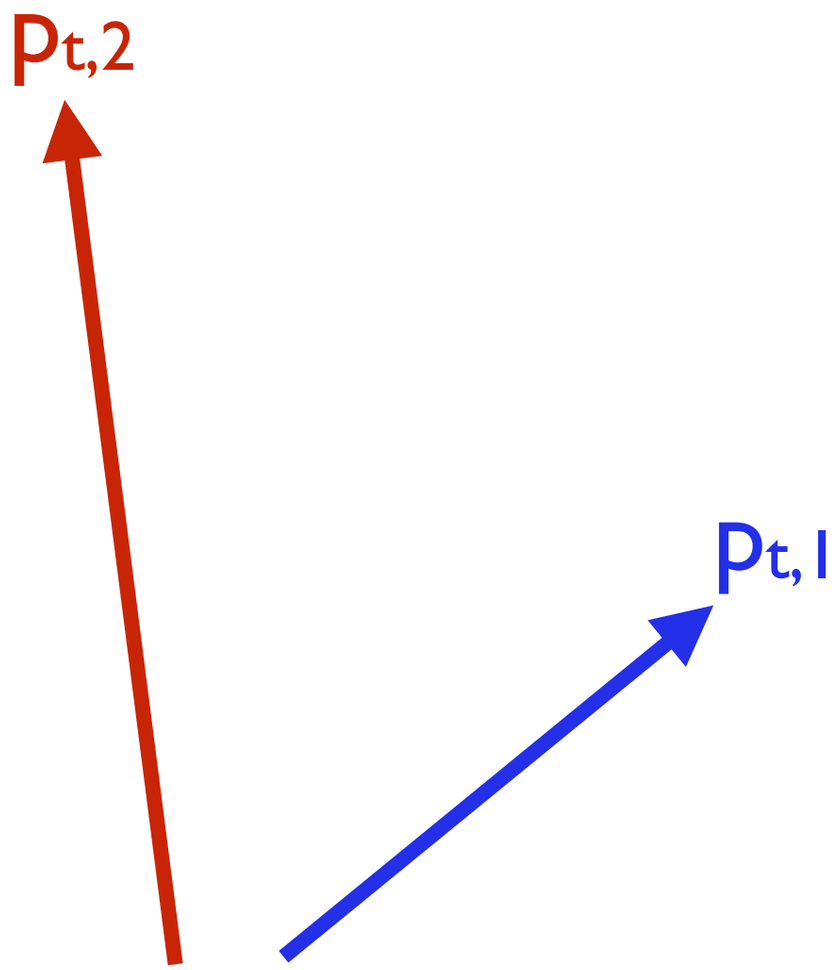

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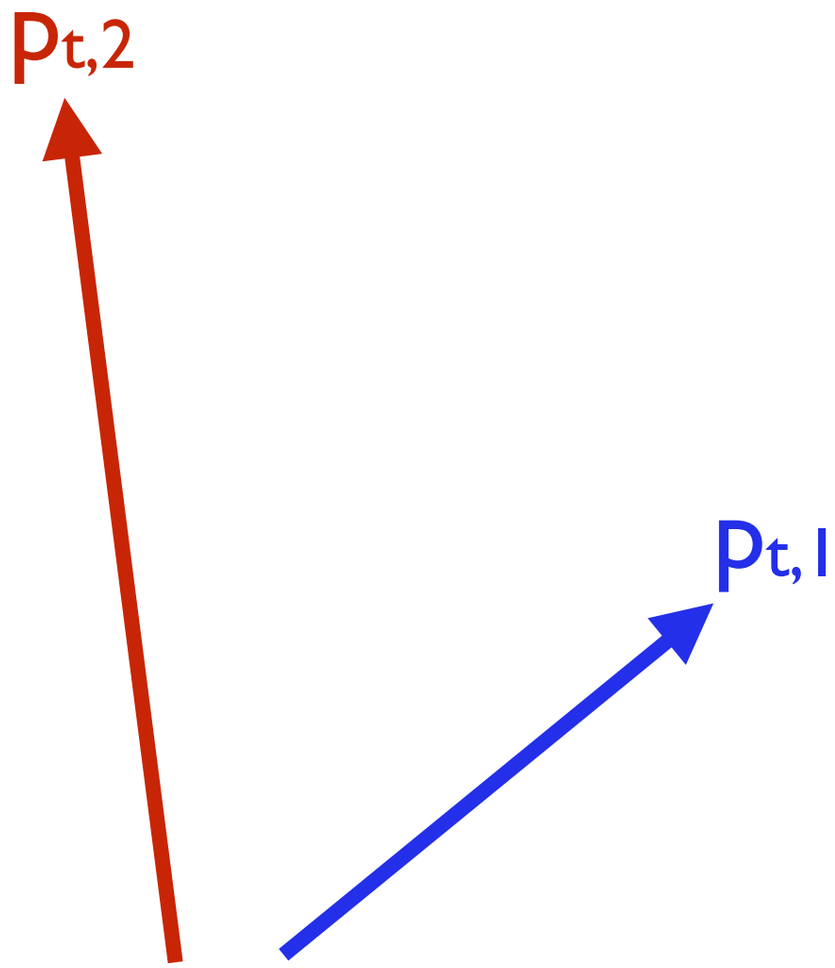

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$$d_{1B} < d_{2B} \qquad d_{12} < d_{1B}\,?$$

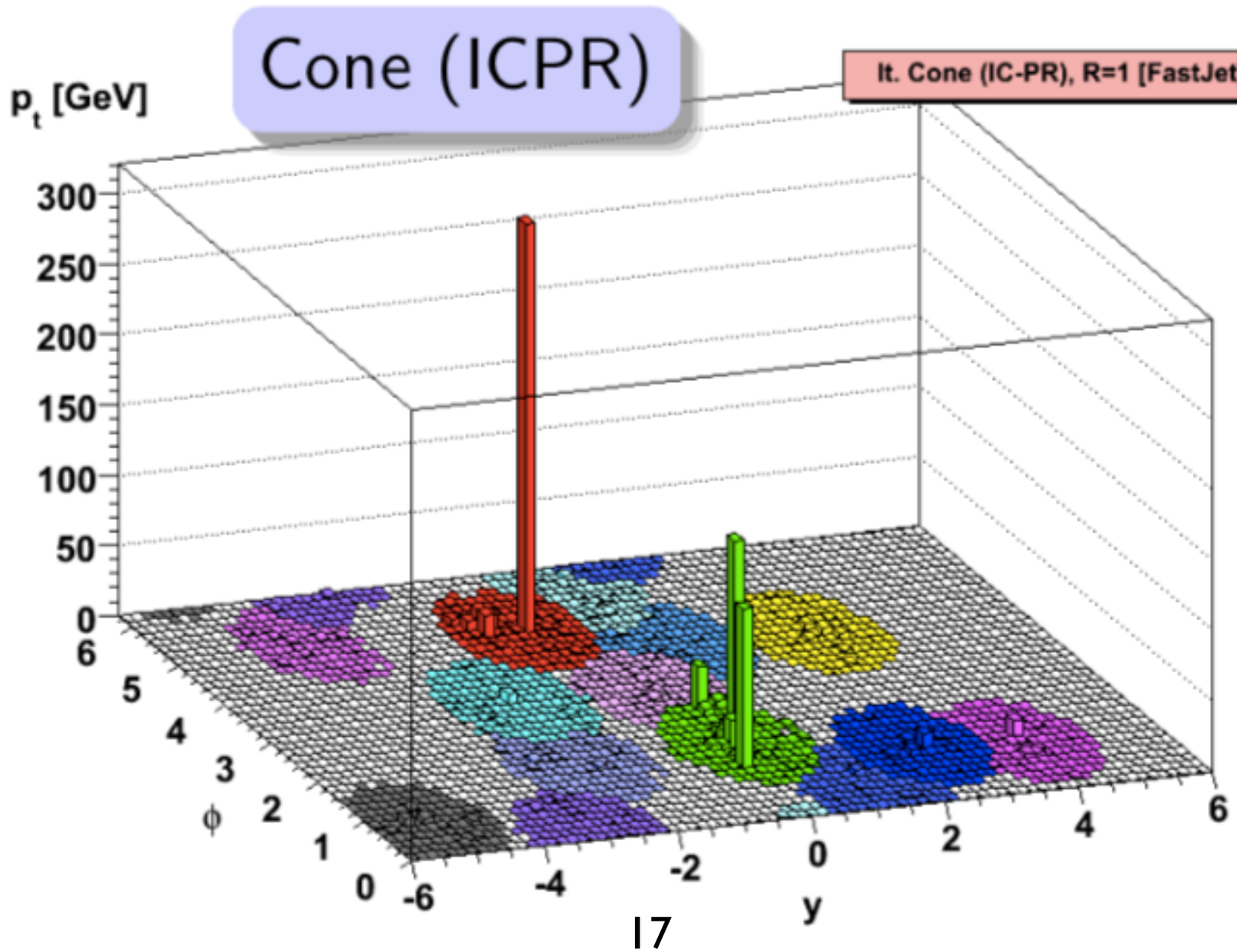
Common Sequential Recombination Algorithms

$$d_{ij} = \min(k_{ti}^{2\mathbf{p}}, k_{tj}^{2\mathbf{p}})\Delta R_{ij}^2/R^2 \qquad d_{iB} = k_{ti}^{2\mathbf{p}}$$

	Alg. name
$p = 1$	k_t CDOSTW '91-93; ES '93
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98
$p = -1$	anti-k_t Cacciari, GPS, Soyez '08 $\sim$ reverse-k_t Delsart

Shape of Jets from These Algorithms

- Although not infrared/collinear safe, cone algorithms give regular jet shapes, which makes it possible to predict acceptance



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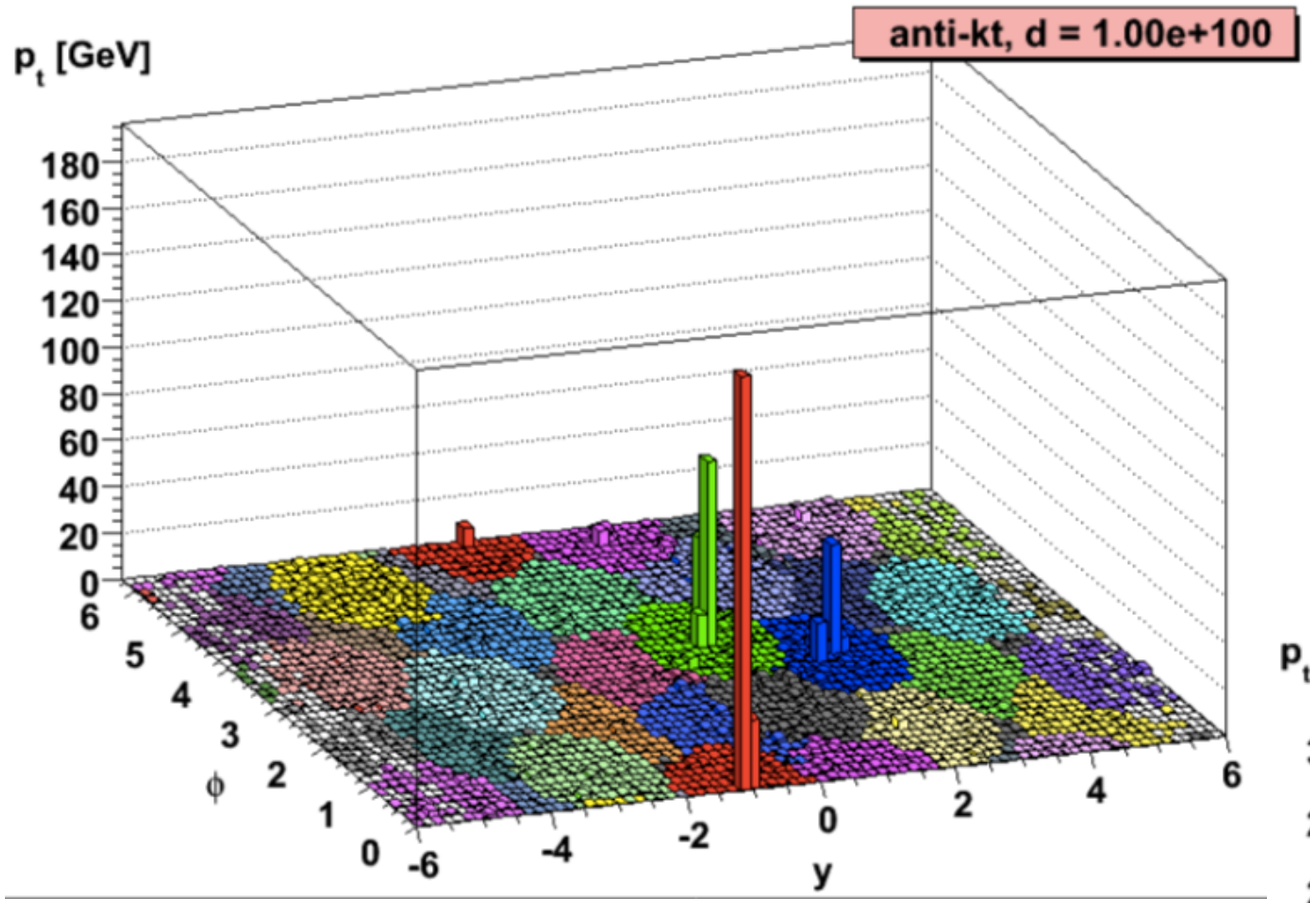

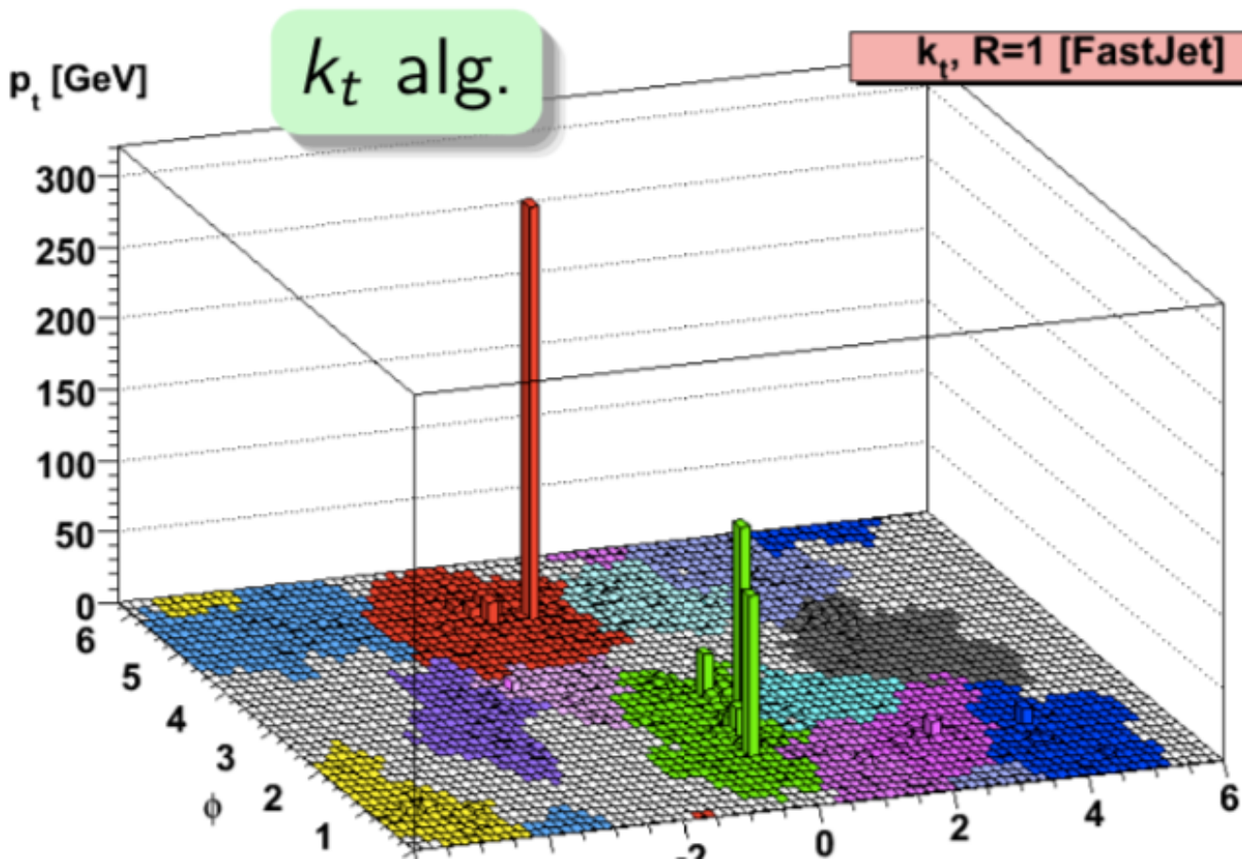

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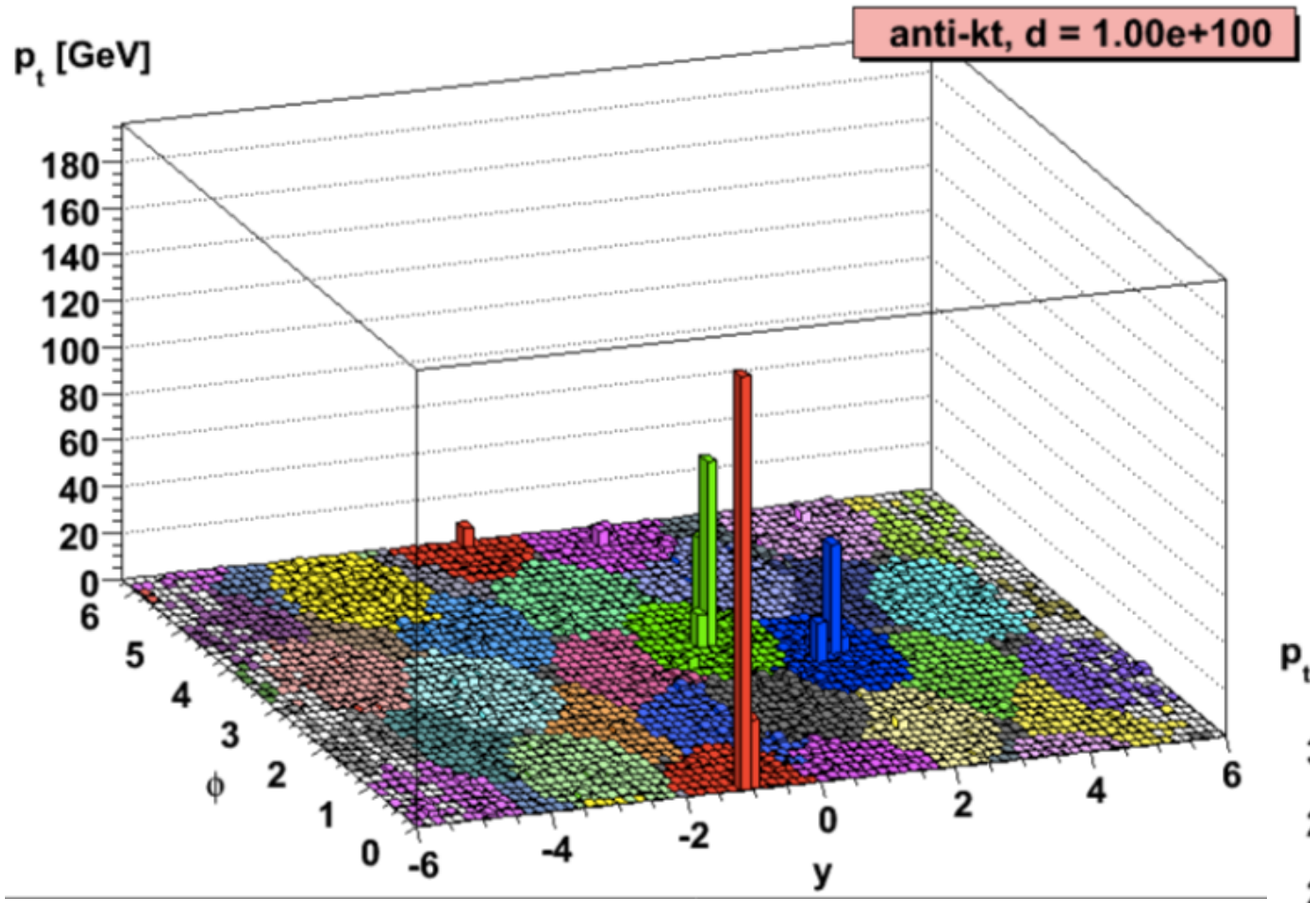
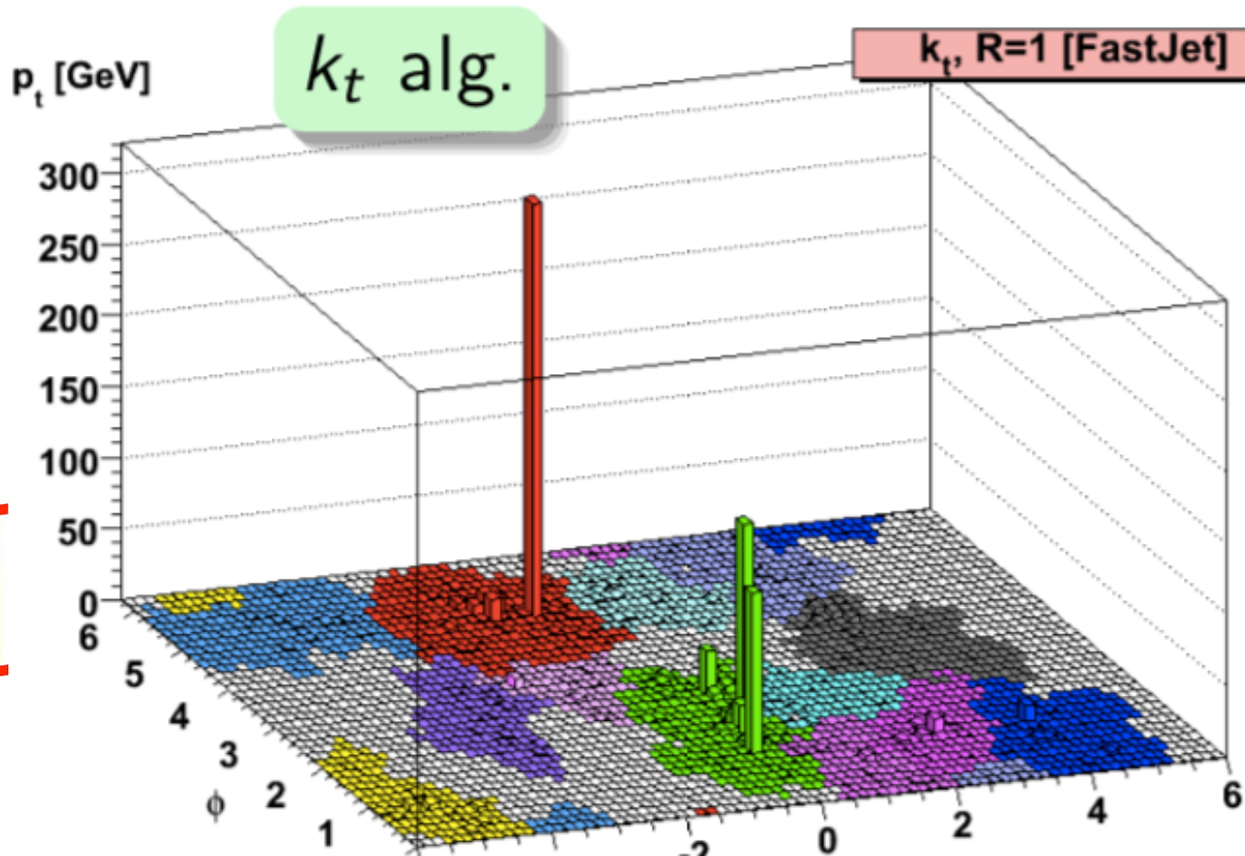


Homework



Comparison of Cone and Sequential Recombination

- See examples from the lectures of Gavin Salam in the attachment

Jet-Related Measurements

Dijet Cross Section Measurements

Triple-Differential Dijet Cross Section

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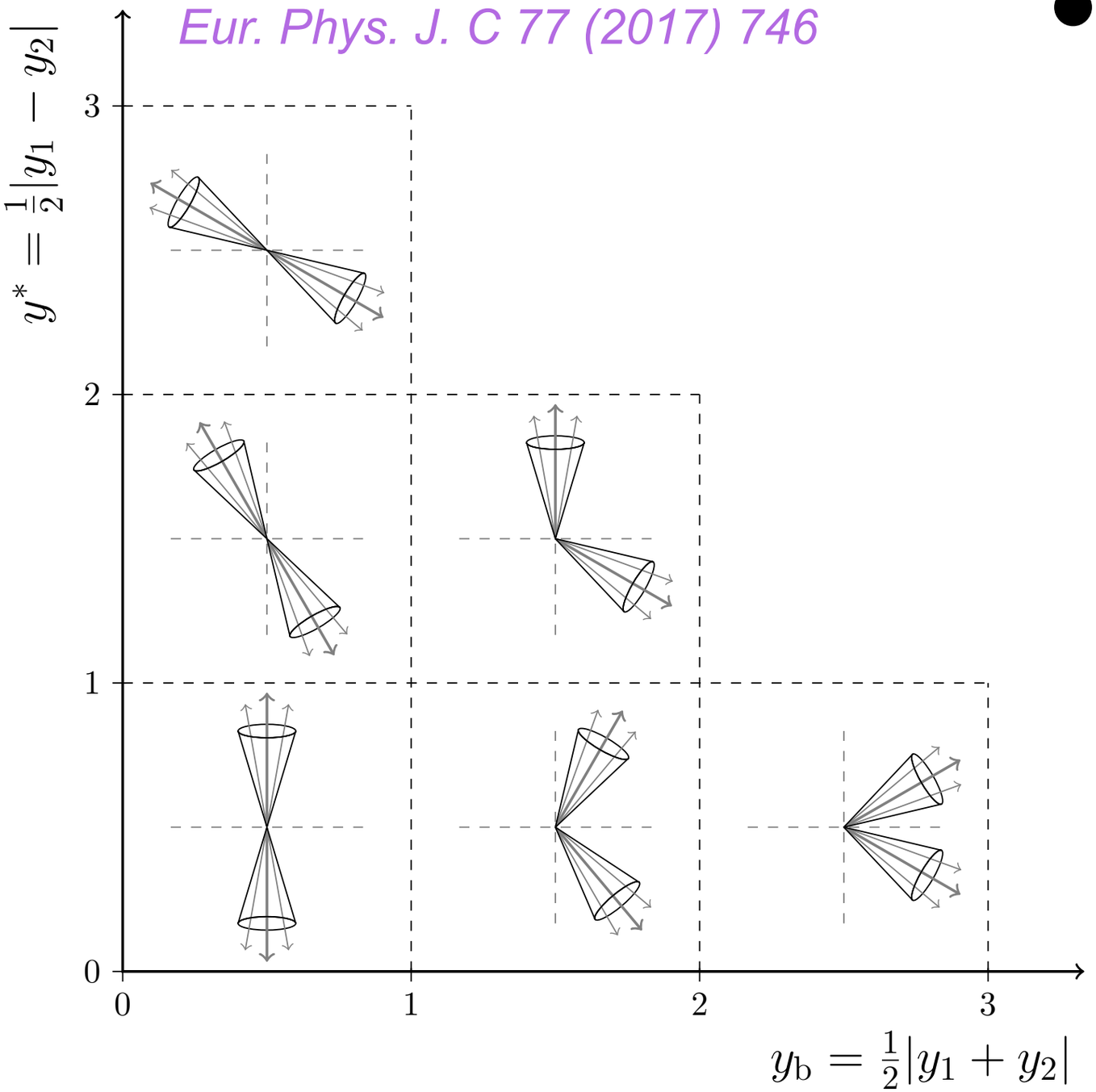

- Three variables

Triple-Differential Dijet Cross Section

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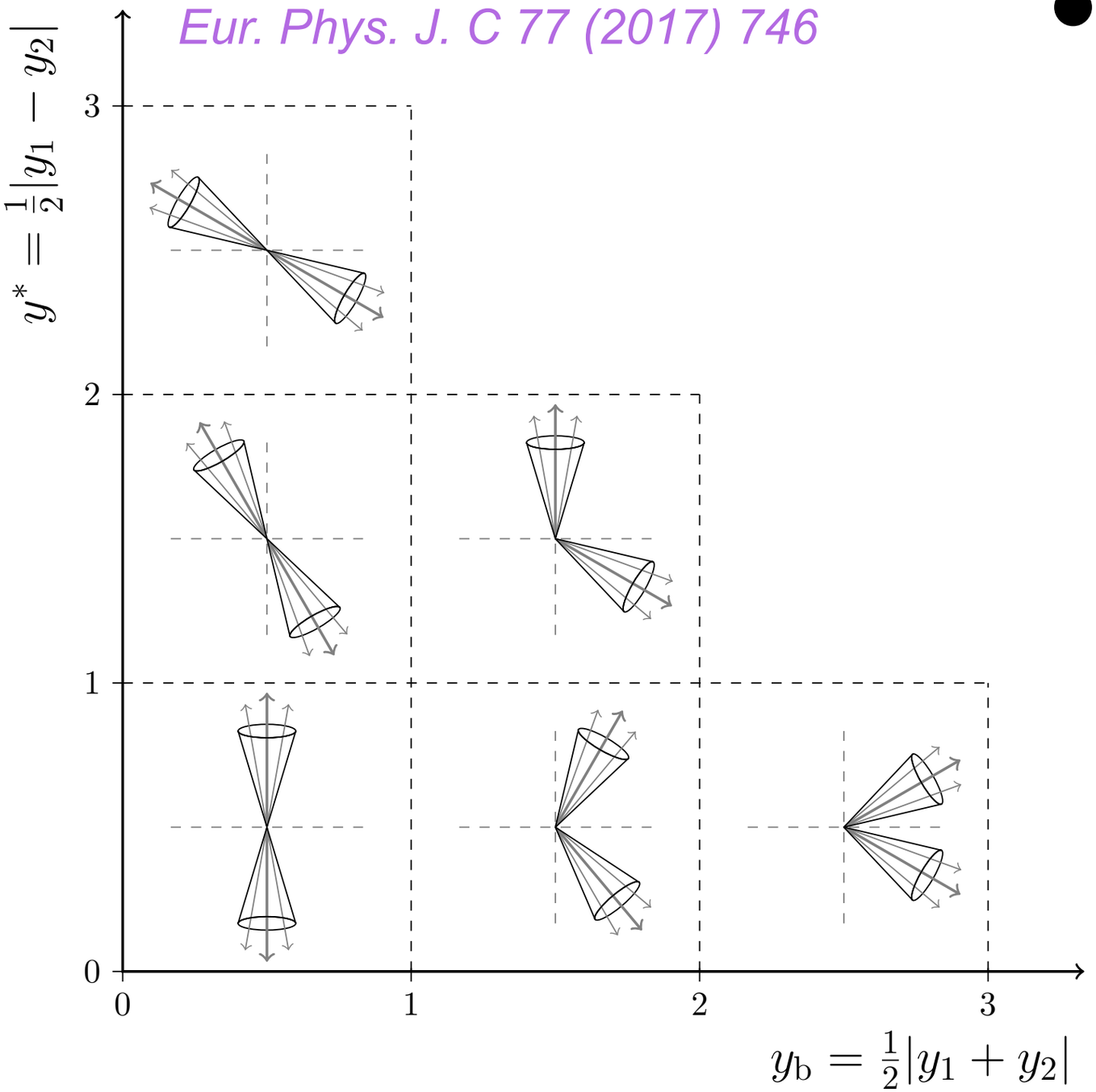

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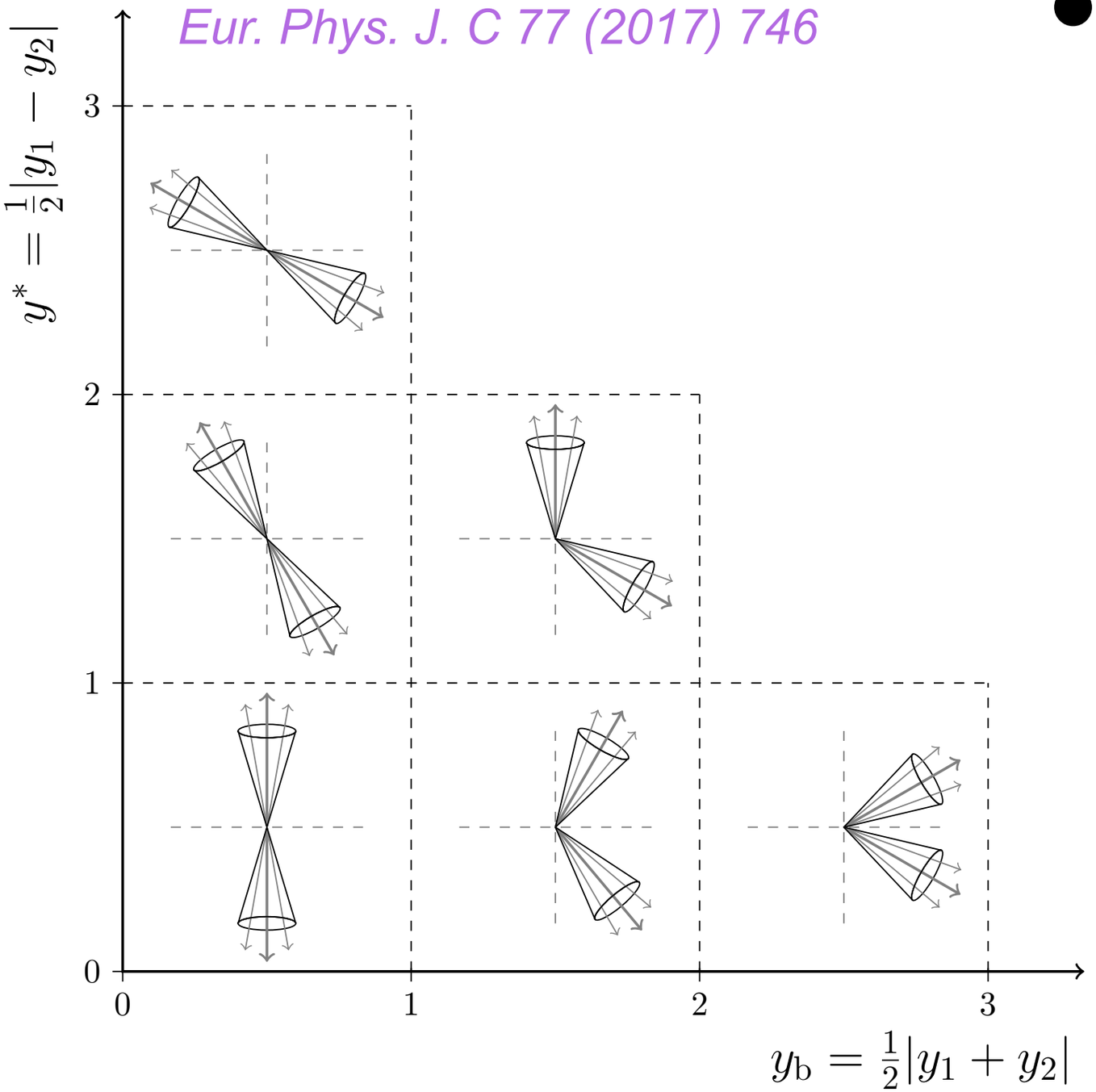

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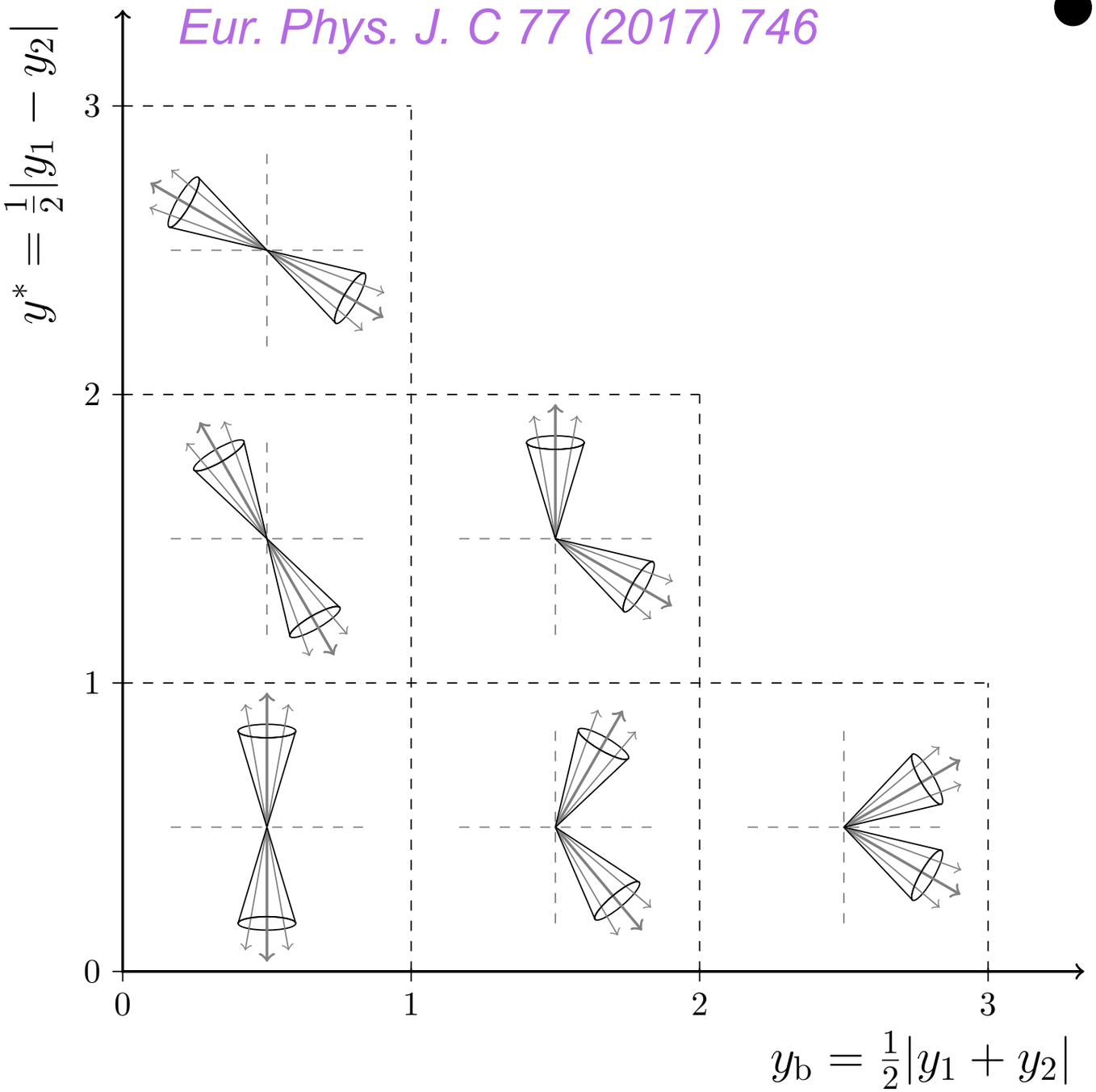

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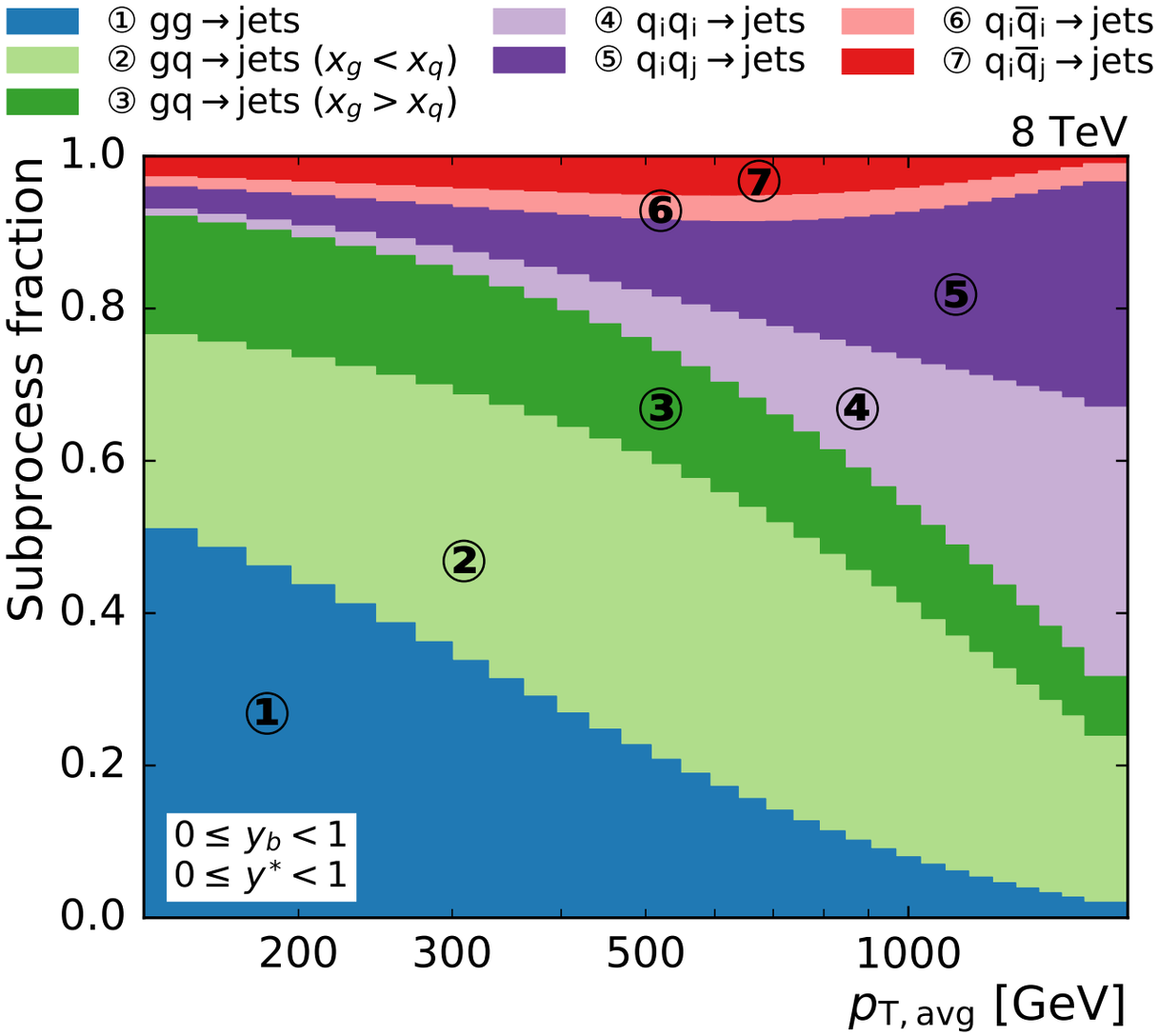

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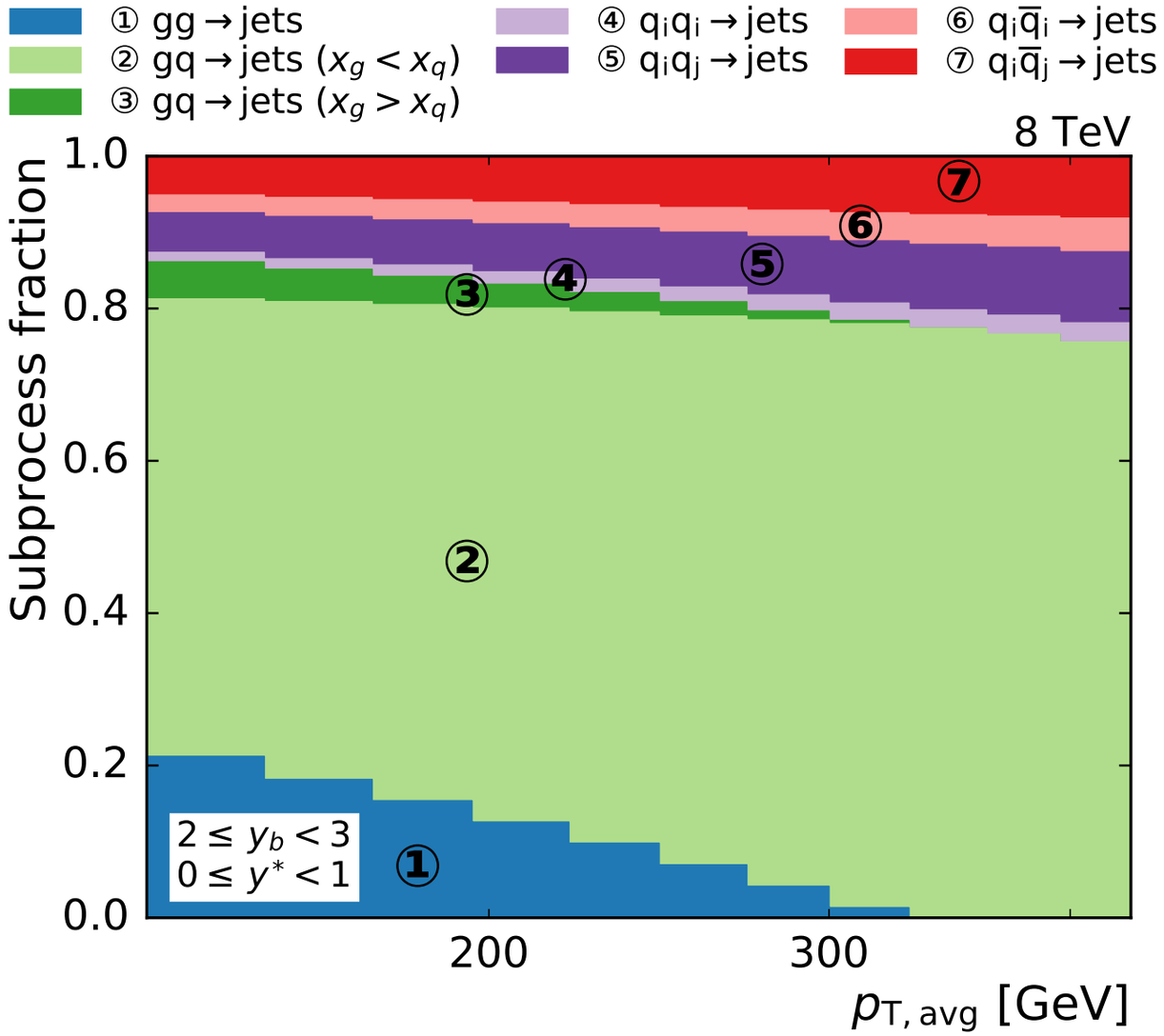

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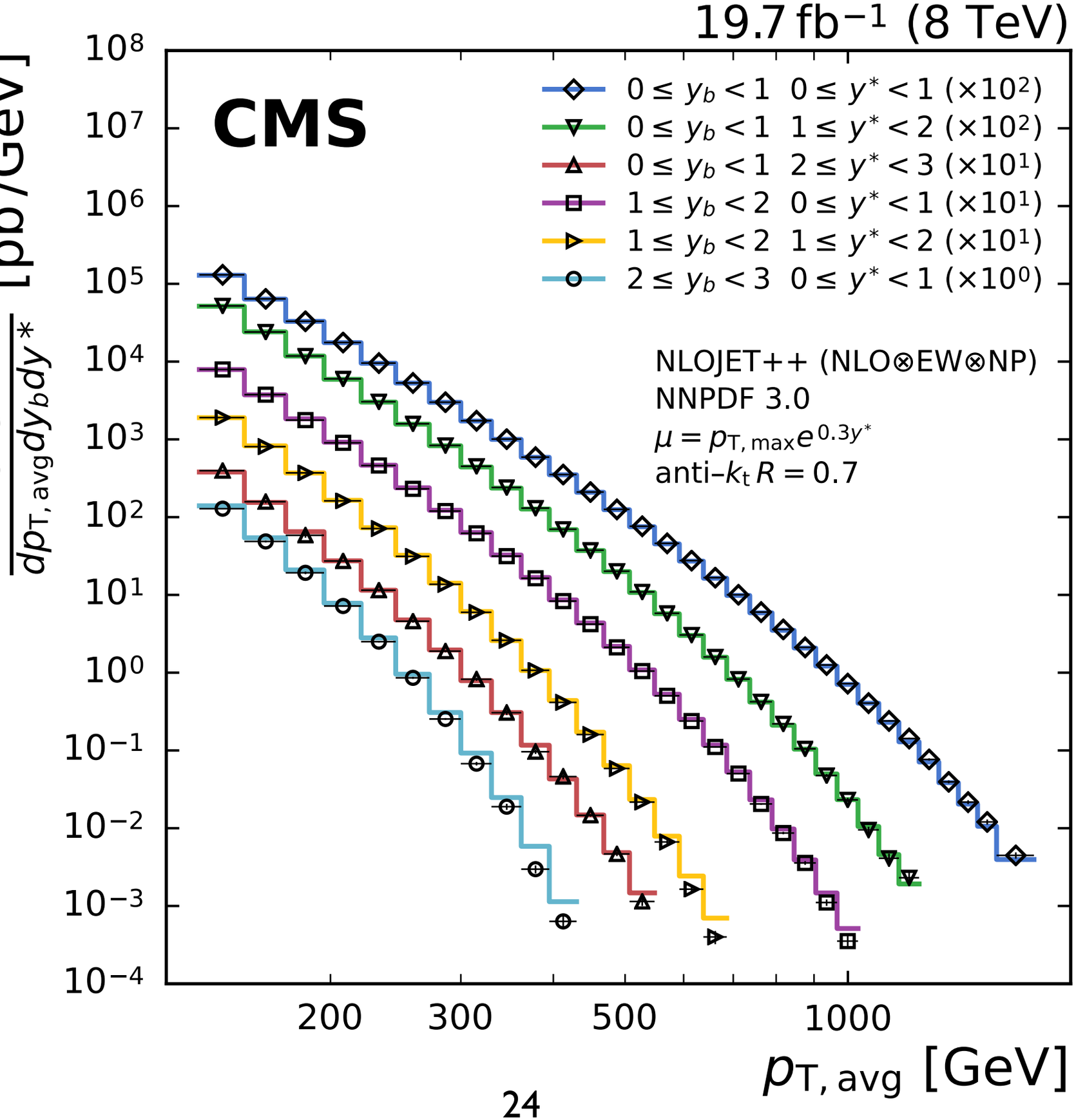
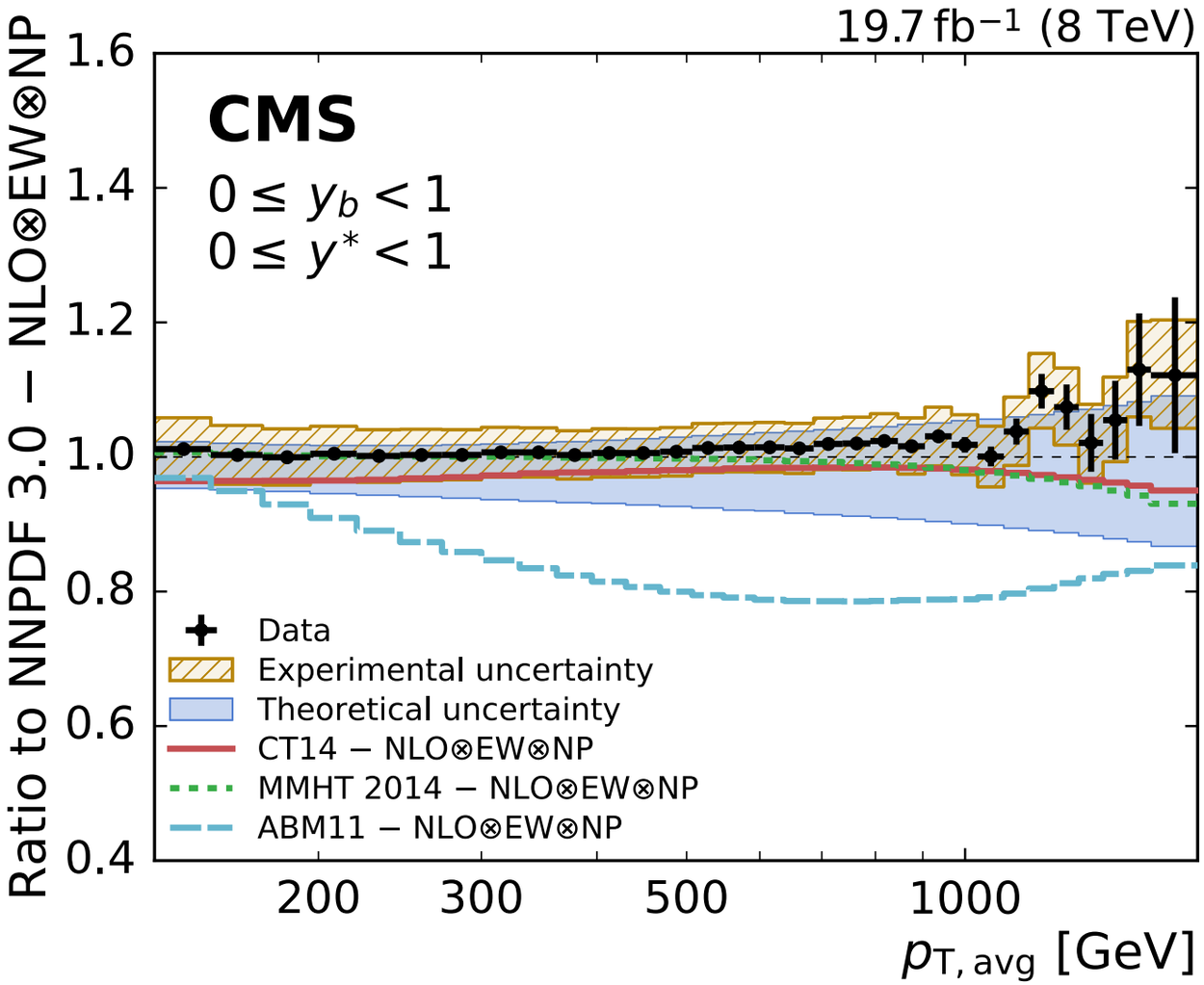
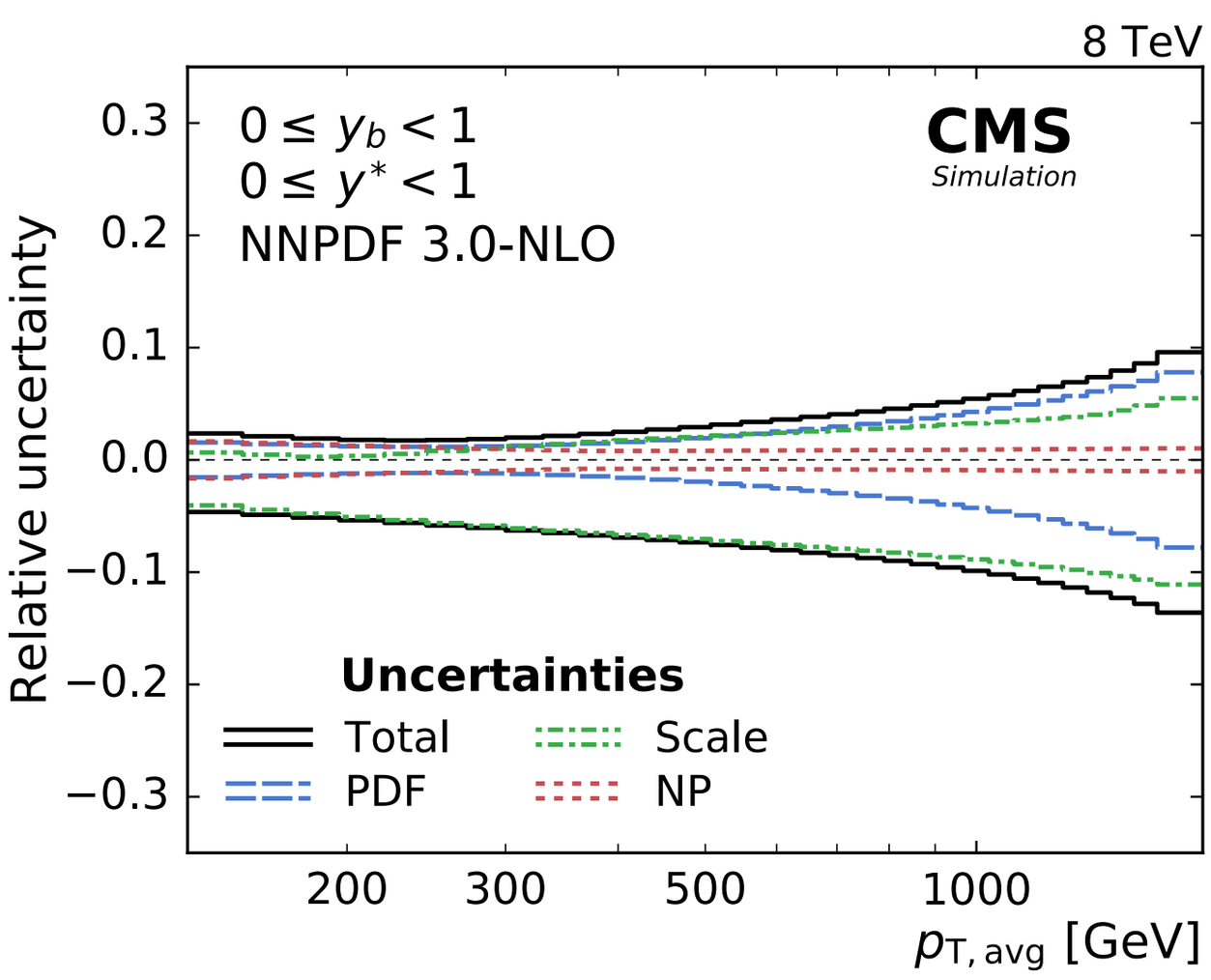
where $p_T = p_{T,1} = p_{T,2}$

Results


19.7 fb^{-1} (8 TeV)
CMS
$0 \le y_b < 1$ $0 \le y^* < 1$ ($\times 10^2$)
$0 \le y_b < 1$ $1 \le y^* < 2$ ($\times 10^2$)
$0 \le y_b < 1$ $2 \le y^* < 3$ ($\times 10^1$)
$1 \le y_b < 2$ $0 \le y^* < 1$ ($\times 10^1$)
$1 \le y_b < 2$ $1 \le y^* < 2$ ($\times 10^1$)
$2 \le y_b < 3$ $0 \le y^* < 1$ ($\times 10^0$)
NLOJET++ (NLO⊗EW⊗NP)
NNPDF 3.0
$\mu = p_{T,\,max} e^{0.3y^*}$
anti-k_t $R = 0.7$
$\frac{d^3\sigma}{dp_{T,\,avg}dy_b dy^*}$ [pb/GeV]
$p_{T,\,avg}$ [GeV]

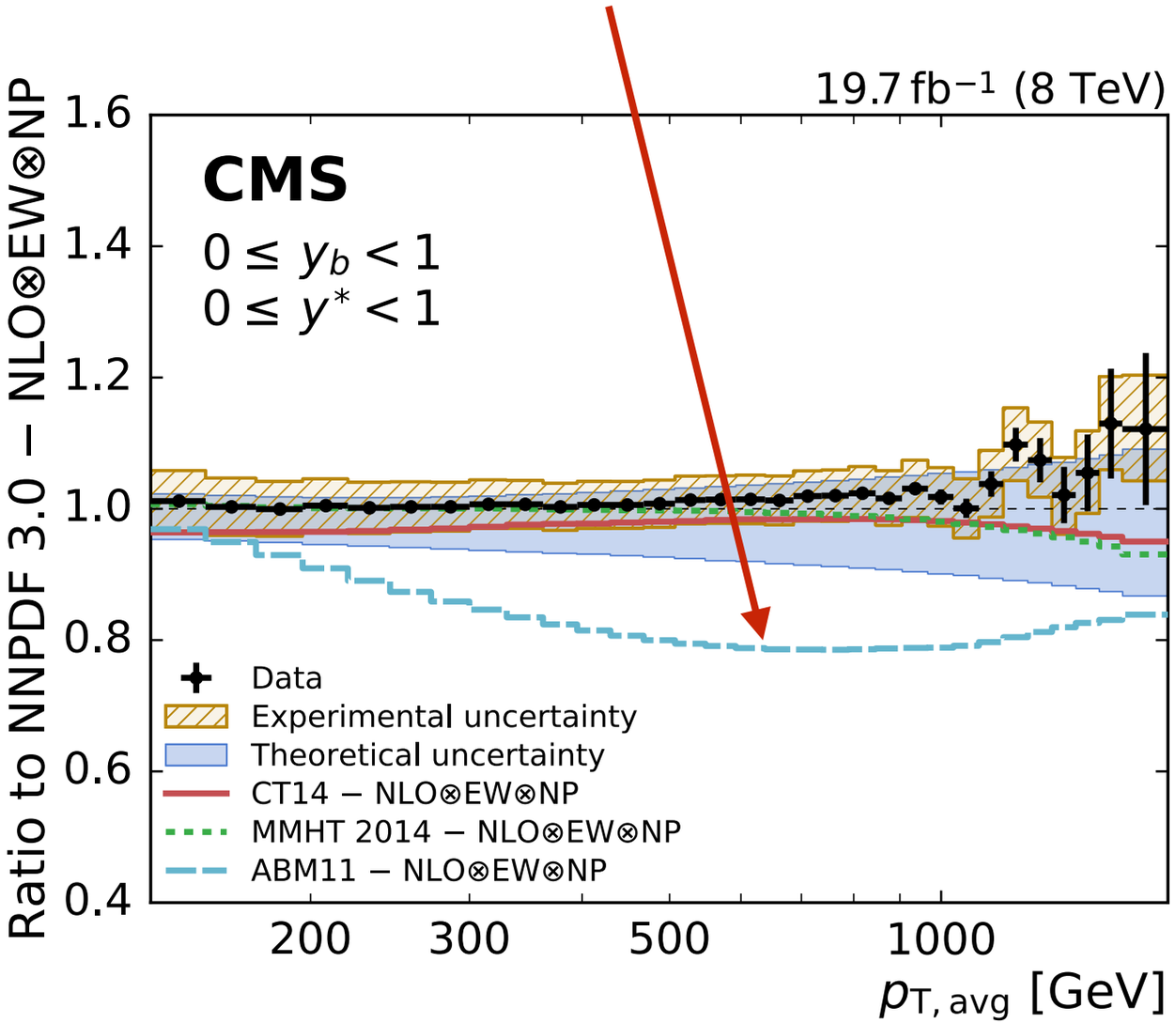
Results at Small y_b

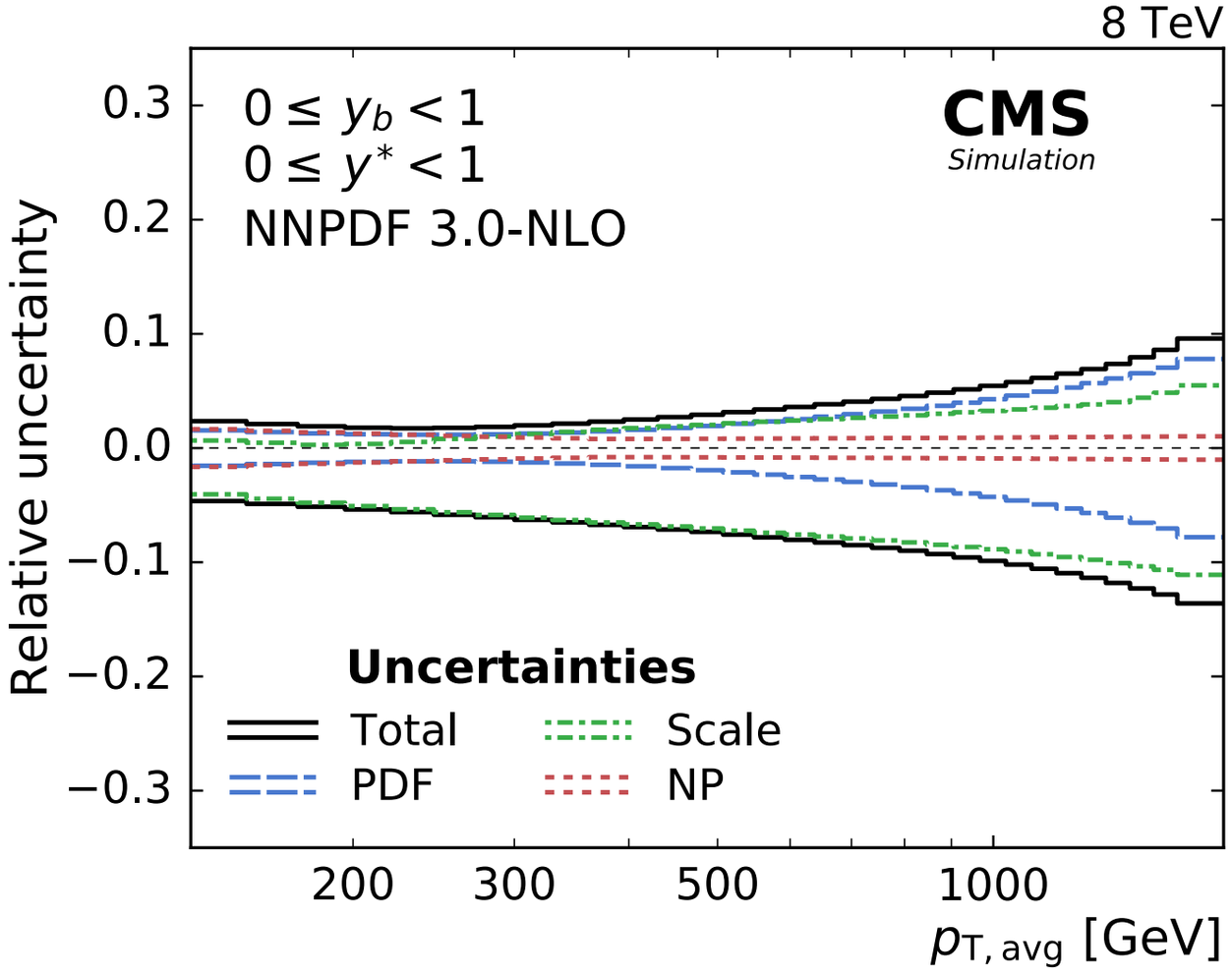




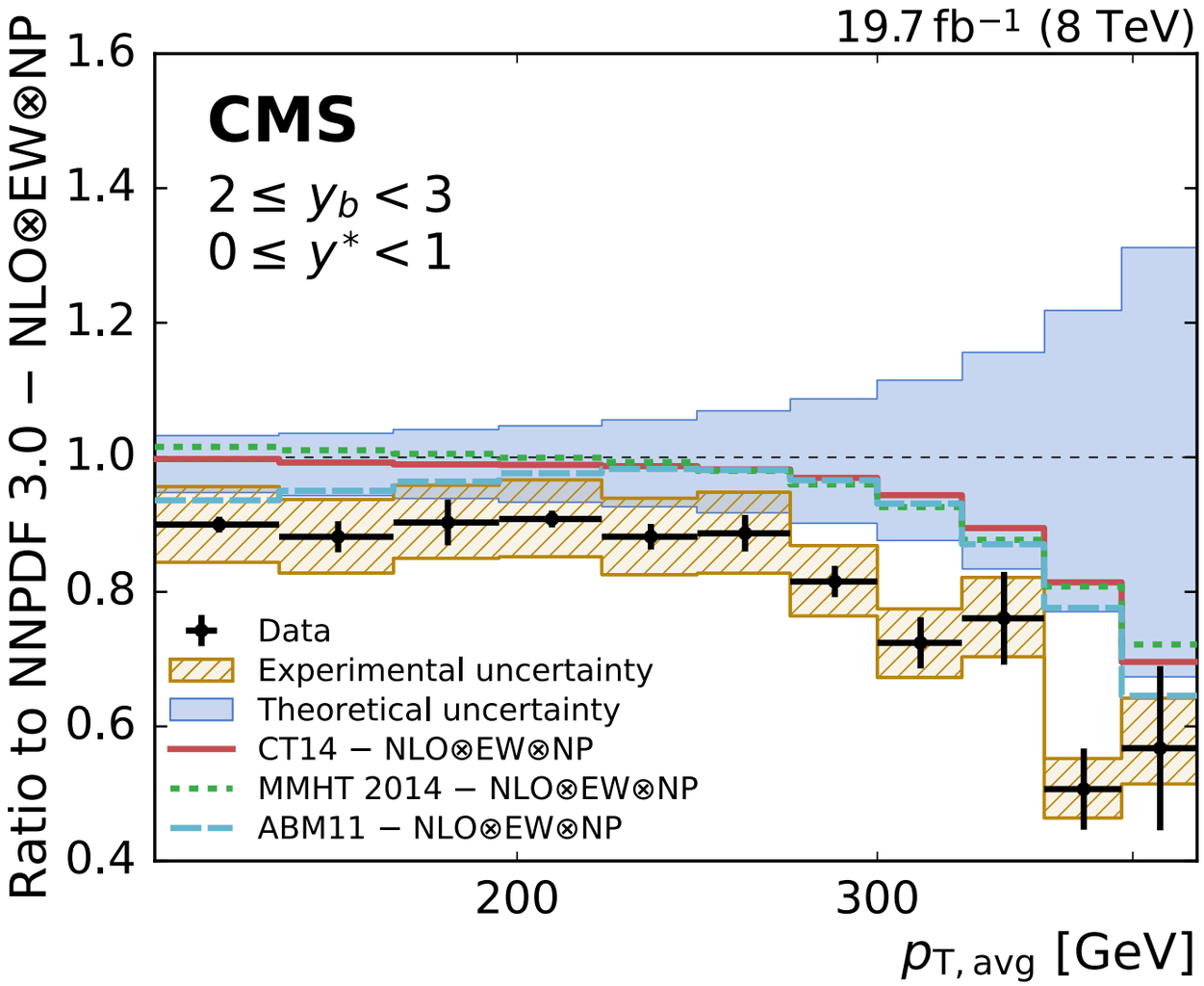
Results at Small y_b

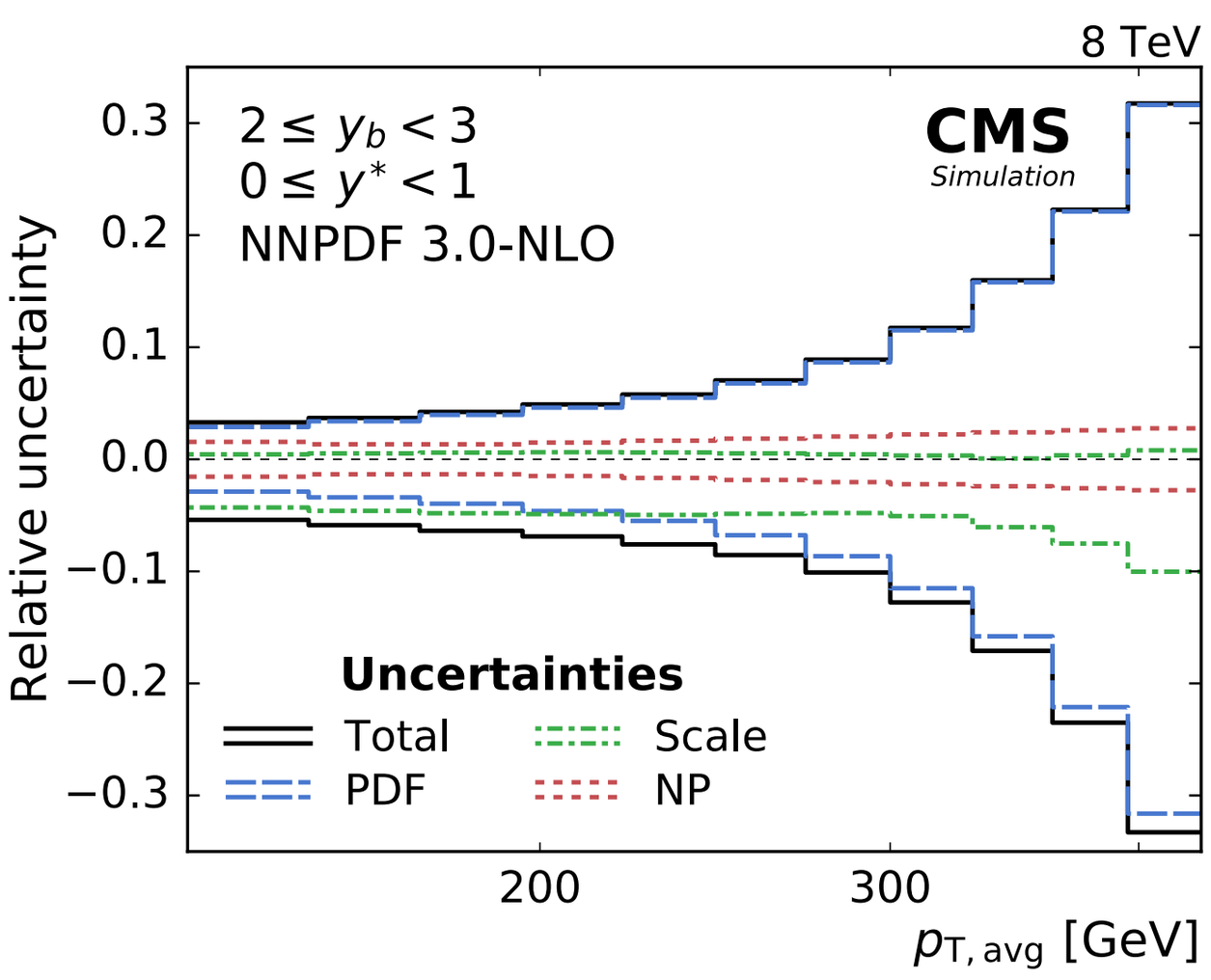
Due to soft gluon PDF and smaller α_s





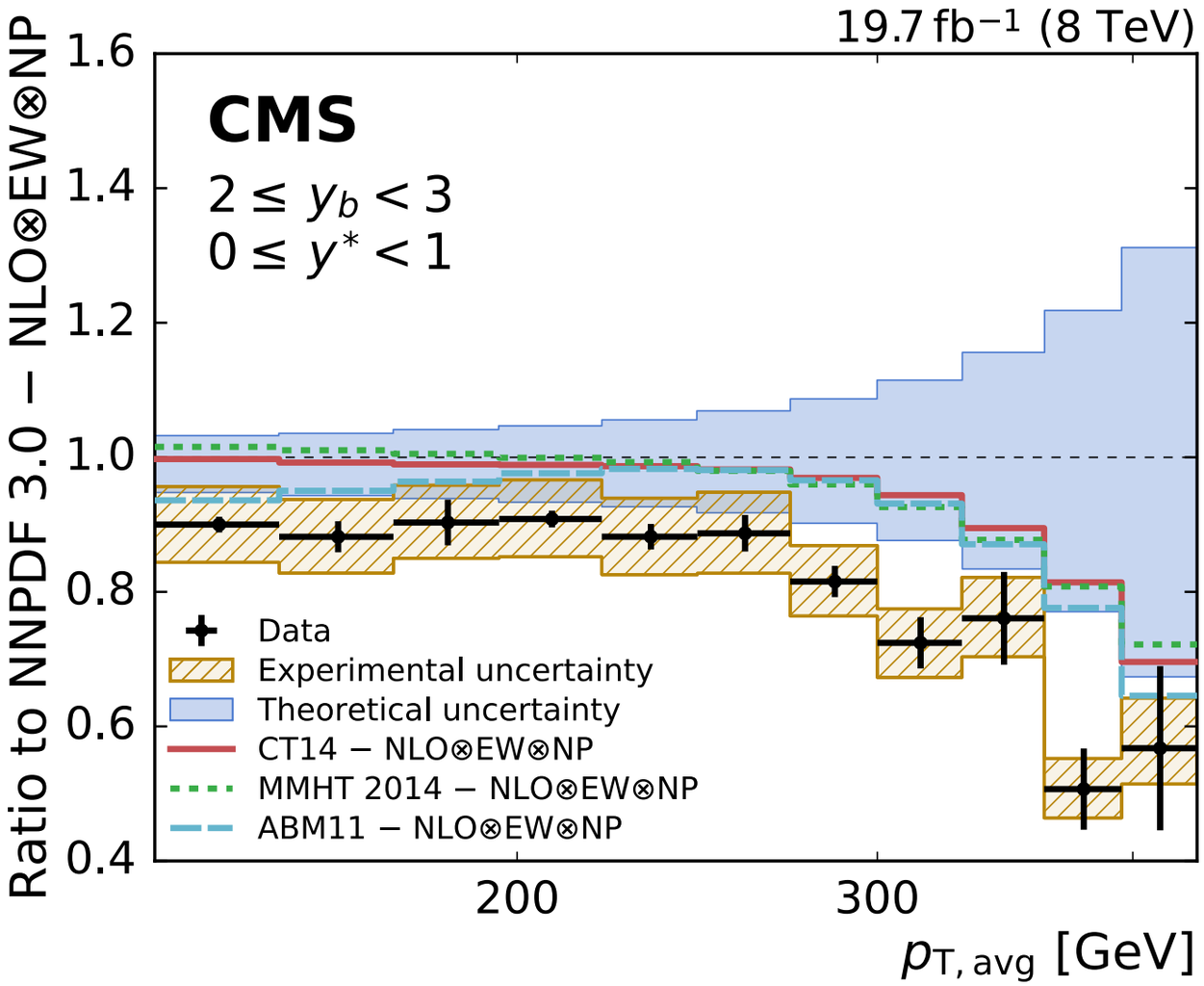
Results at Large y_b

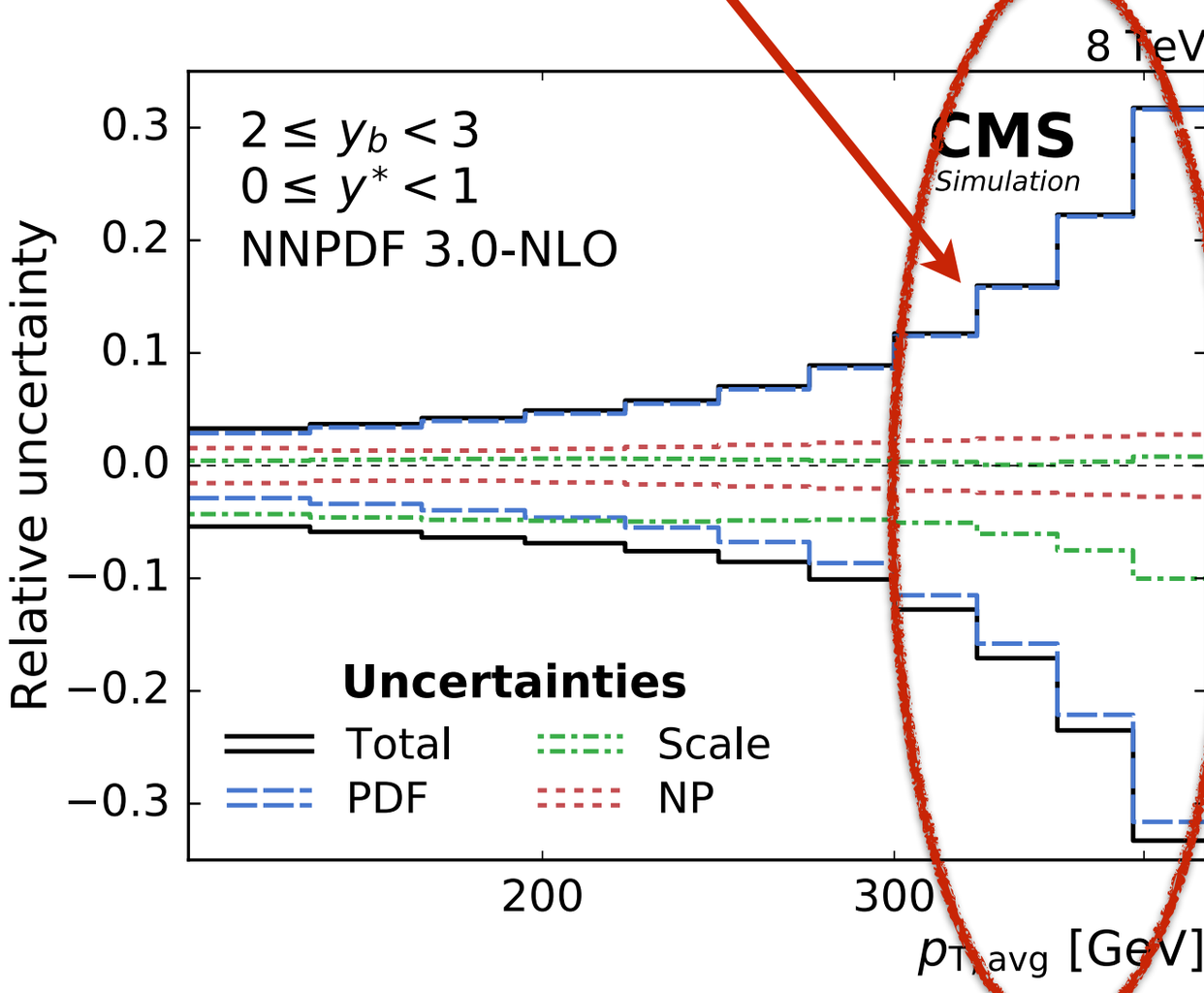




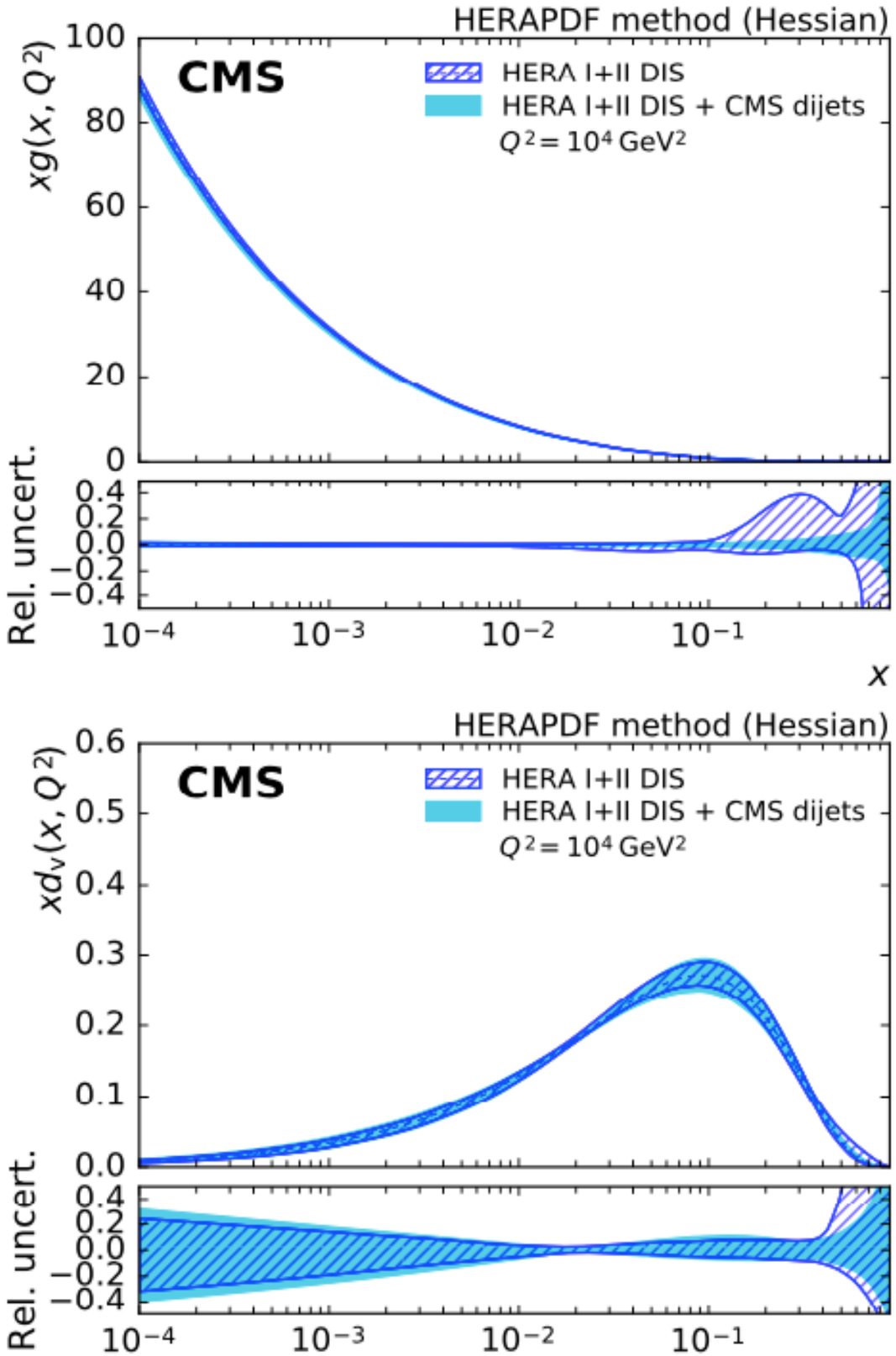
Results at Large y_b

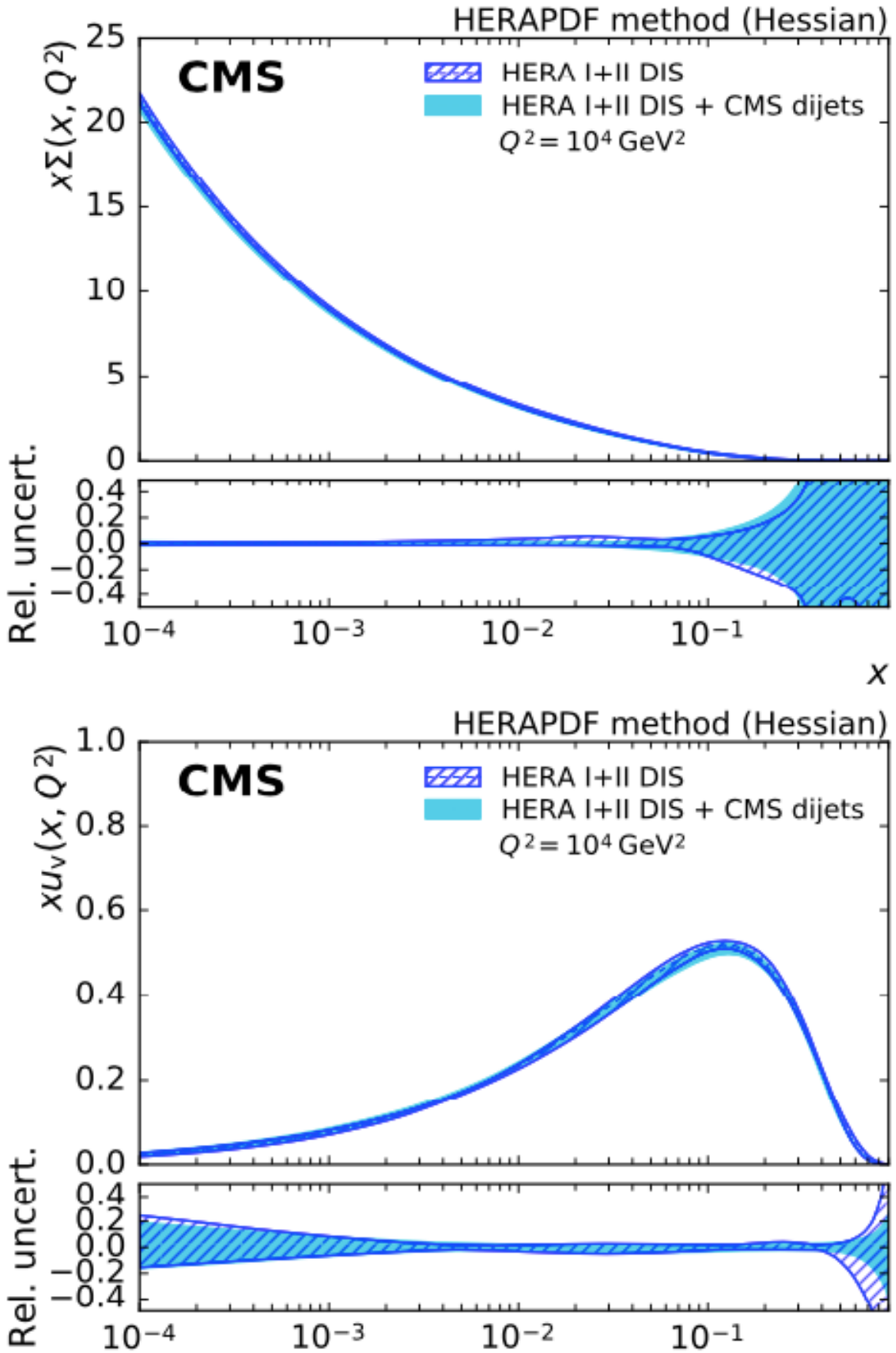
Where experimental results could contribute



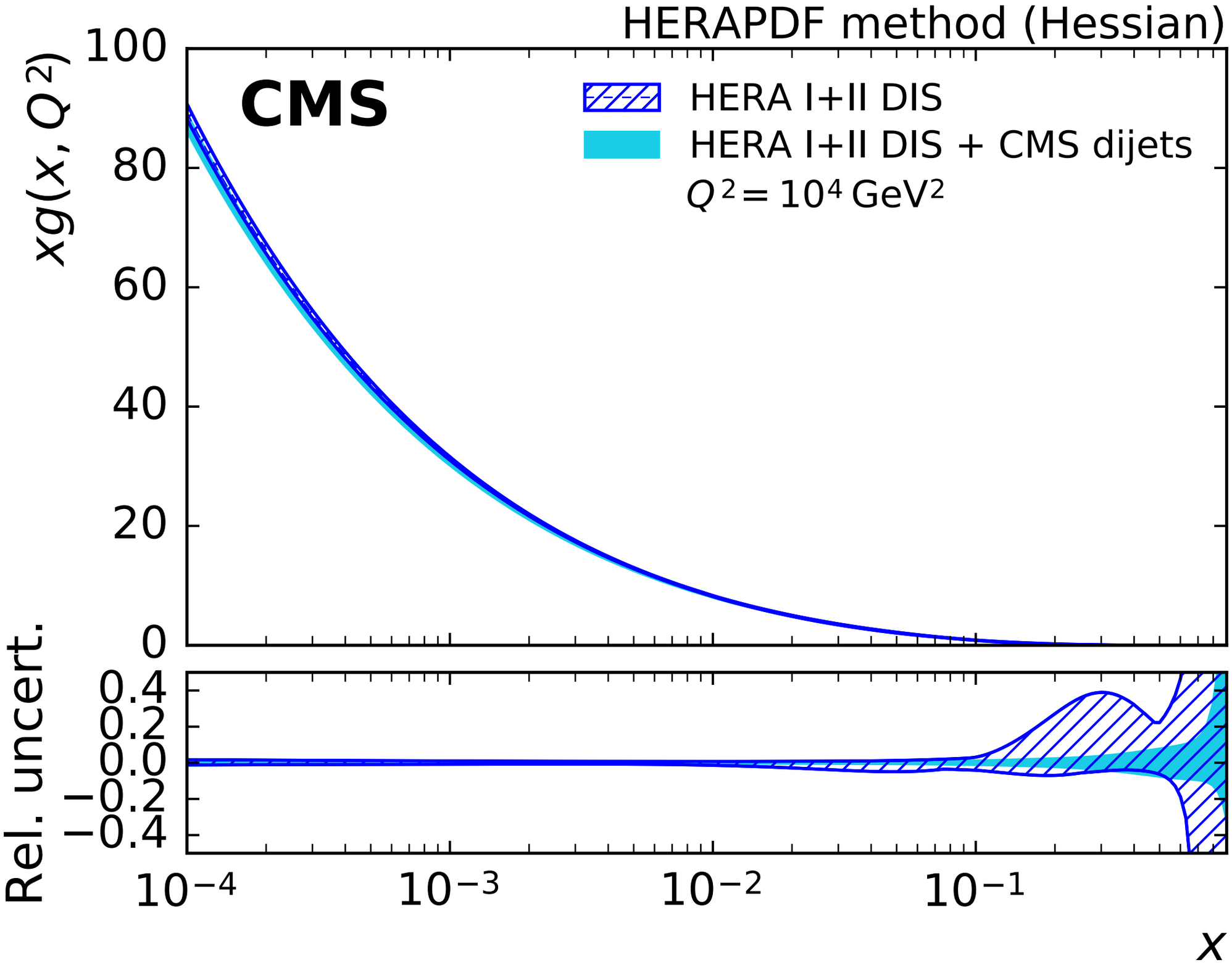


Contraint on PDFs





Contraint on PDFs



Extrapolation to Gluon PDFs at Lower Q^2