Pythia
(ピューティアー)

Pythia ⟷ Belle II

Peter Skands (University of Oxford & Monash University)

PART 1

1. Introduction to Event Generators
2. Constraining Pythia at LEP $\longleftrightarrow q\bar{q}$ continuum
3. Pythia for B Decays

PART 2

4. Tuning Approaches
5. The MCPLOTS event-generator validation resource

THE UNIVERSITY OF WARWICK
THE ROYAL SOCIETY
VINCIA
Australian Government
Australian Research Council
MCnet

Event Generators: Divide and Conquer

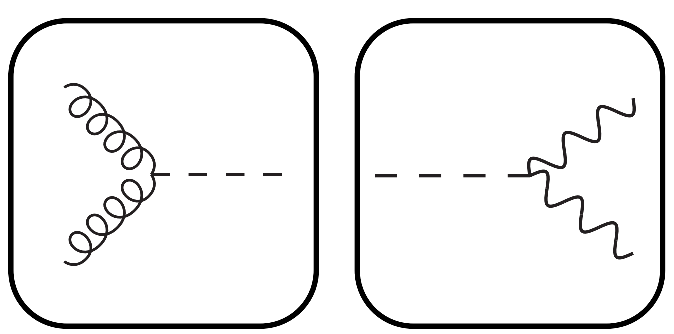
Model full event structure by repeated/nested factorizations

→ Split the problem into many ~ simple pieces

$$\mathscr{P}_{\text{event}} = \underbrace{\mathscr{P}_{\text{Hard}} \otimes \mathscr{P}_{\text{Res}} \otimes \mathscr{P}_{\text{FSR}} \otimes \mathscr{P}_{\text{Had}} \otimes \mathscr{P}_{\text{Dec}} \otimes \ldots}$$

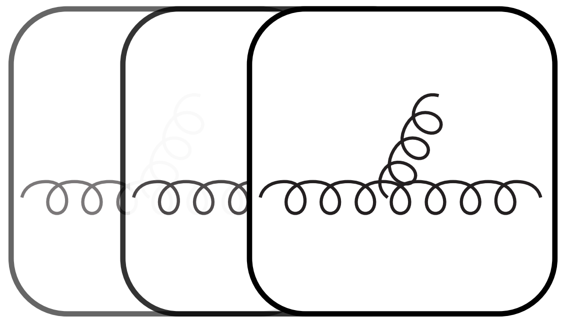
Quantum mechanics → **Probabilities** → Make **Random Choices** (as in nature)

→ **Markov-Chain Monte Carlo** → *"Event Generators"*



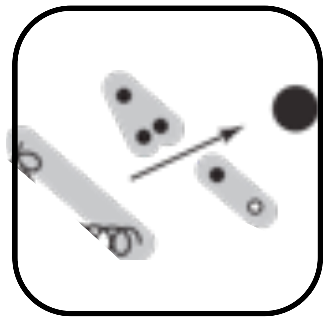
Hard Process & Decays:

Process-specific (N)LO matrix elements → Sets "Hard" scale: Q_{MAX}



Accelerated Charges → Perturbative Bremsstrahlung:

Differential evolution, dP/dQ^2, from Q_{MAX} to $Q_{\text{Hadronization}}$ ~ 1 GeV



Hadronization (and hadron decays)

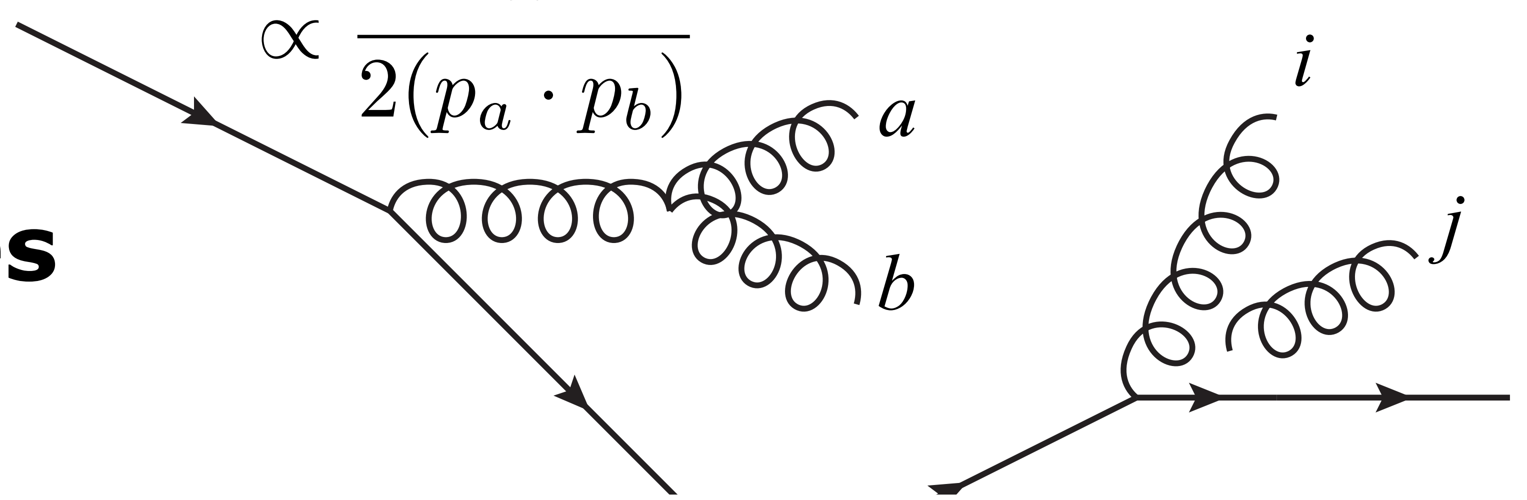
Non-perturbative model of color-singlet parton systems → hadrons

1) Bremsstrahlung via Parton Showers

see e.g PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Most bremsstrahlung is driven by divergent propagators → simple structure

Mathematically, **gauge amplitudes factorize** in singular limits



Partons ab → **collinear**:

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \overset{a||b}{\to} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

$P(z)$ = **DGLAP splitting kernels**", with $z = E_a/(E_a+E_b)$

Gluon j → **soft**:

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g\to 0}{\to} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

Coherence → Parton j really emitted by (i,k) "dipole" or **"antenna" (eikonal factors)**

These are the **building blocks of parton showers** (DGLAP, dipole, antenna, …)

(+ running coupling, unitarity, and explicit (E,p) conservation.)

Shower Uncertainties: Non-Singular Variations in Pythia 8

Parton Showers rely on Factorisations in Soft/Collinear Limits

$$|M_{n+1}|^2 \to \sum_{\text{radiators}} a_{\text{sing}} |M_n|^2$$

Approximations based on universal singular structures of gauge theories.

Driven by $1/Q^2$ poles from propagators, with spin-dependent numerators

Renormalization-scale variations **only** produce terms ∝ to these "kernels"

But genuine matrix elements also have "non-singular terms"

Our solution [**Vincia** 1102.2126; **Pythia** 1605.08352]

Non-singular variations

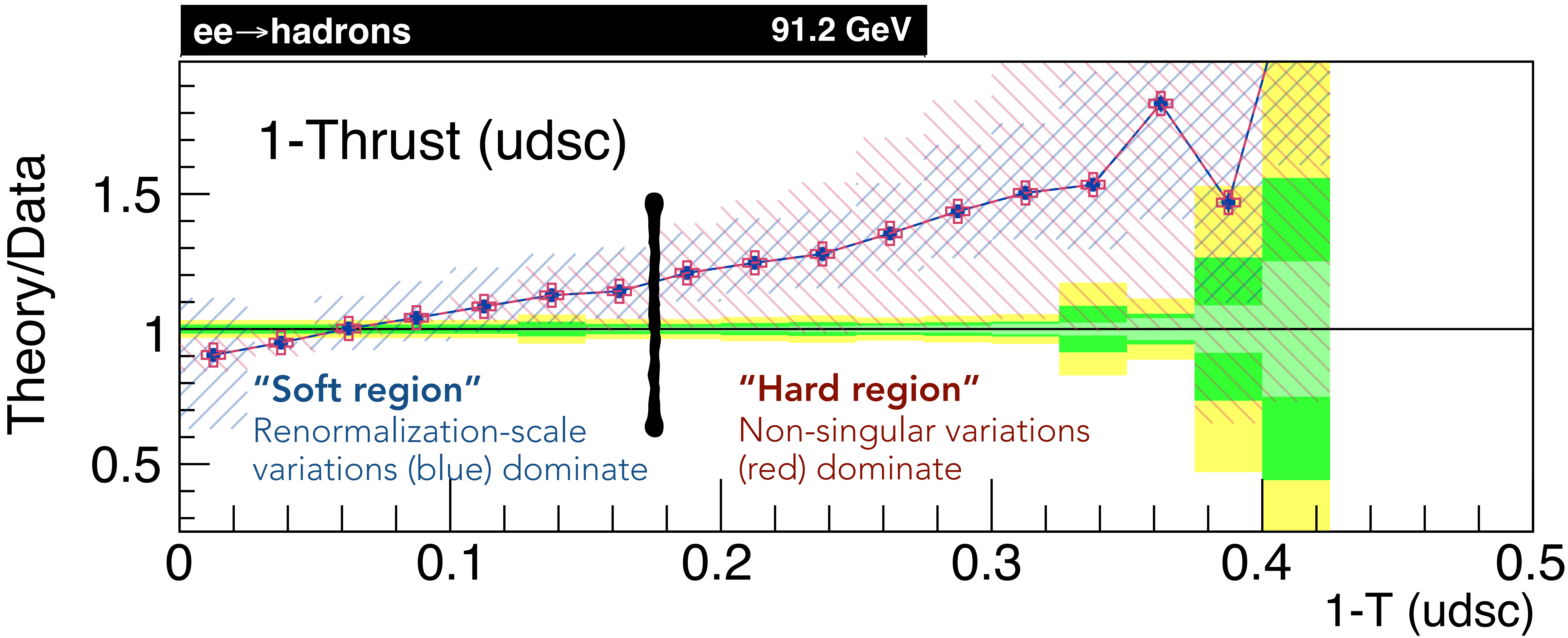
$$a_{\text{sing}} \to a_{\text{sing}} + \Delta a_{\text{non-sing}}$$

Can also be helpful to estimate need for higher matching/merging

Non-Singular Variations: Example

Example from Mrenna & **PS**, Automated Parton-Shower Variations in Pythia 8, 1605.08352

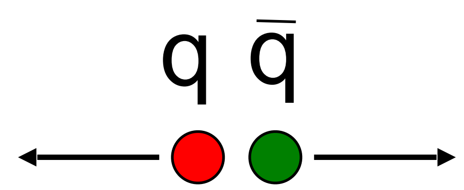
Can vary **renormalisation scale** and **non-singular terms** independently



Note: ME corrections were switched off for illustration. Would reduce red band, but not blue.

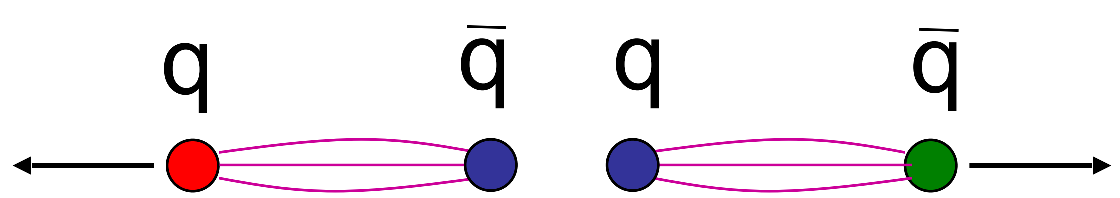
2) Hadronization and Jets

Consider a quark and anti-quark produced in e+e- annihilation

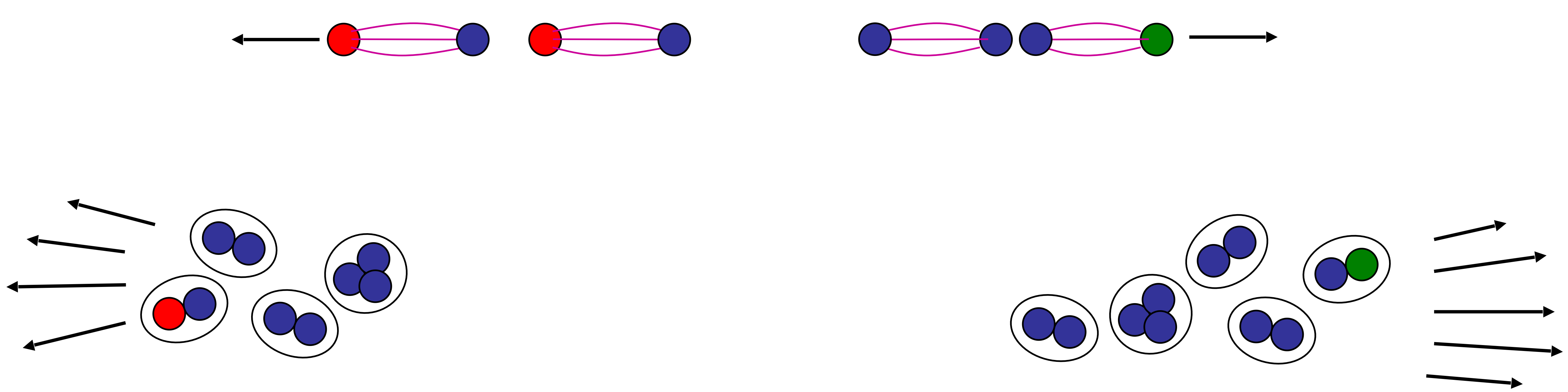


i) Initially Quarks separate at high velocity

ii) Colour flux tube forms between quarks



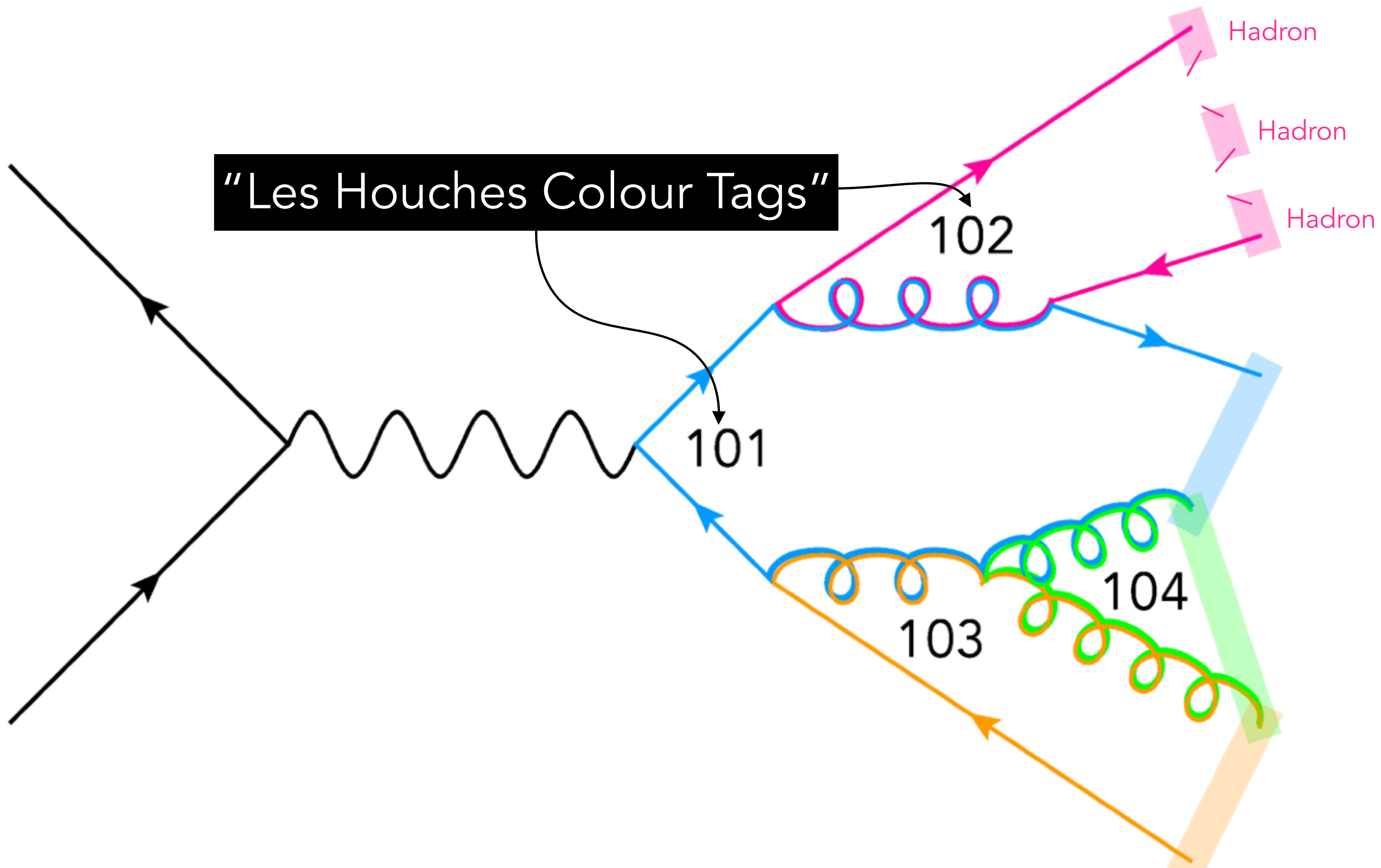
iii) Energy stored in the flux tube sufficient to produce new $\bar{q}q$ pairs



iv) Process continues $\Longrightarrow$ Jets of colourless hadrons

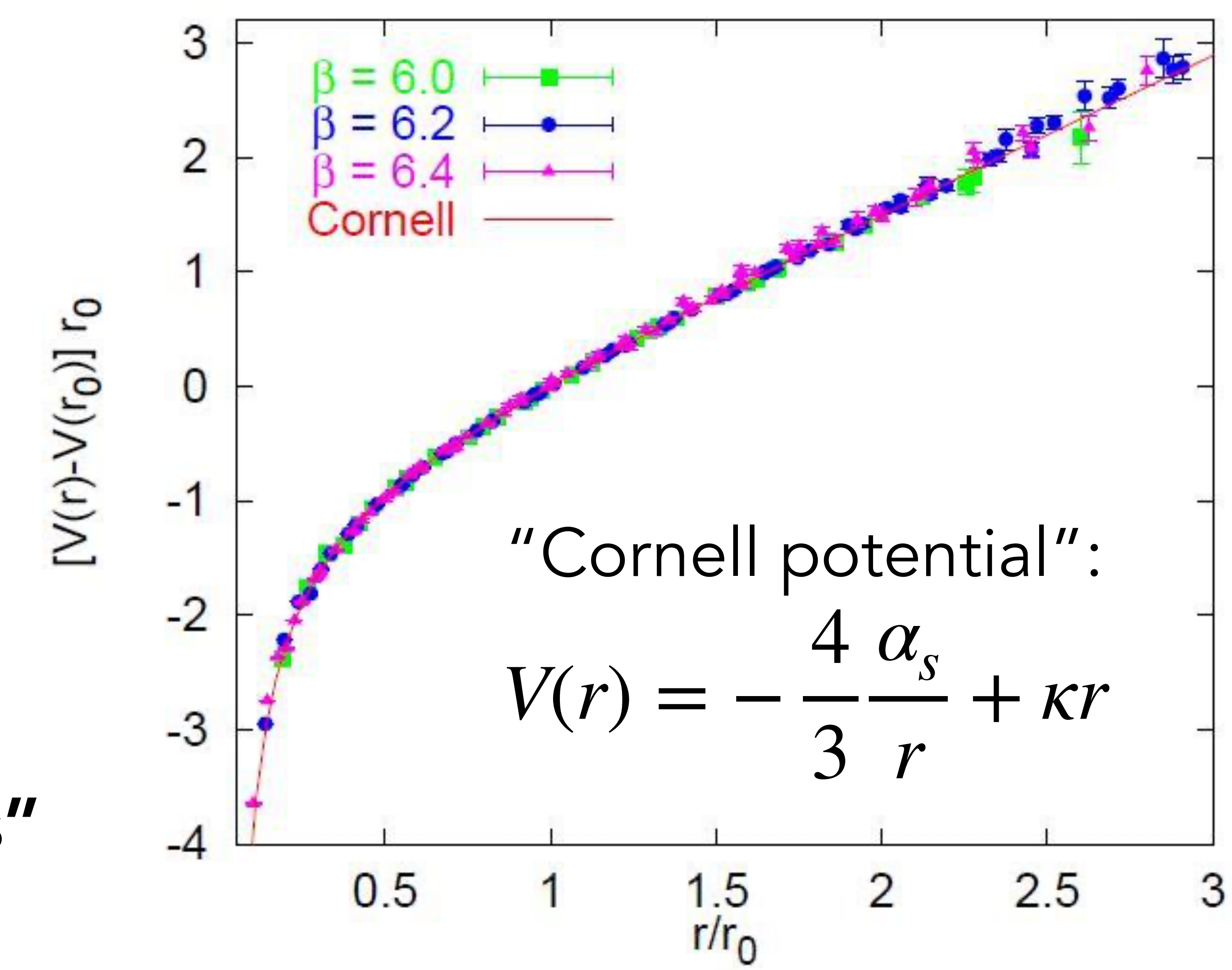
Confinement in PYTHIA: *The Lund String Model*

Simplified (leading-N_C) **"colour flow"** ➜ determine between which partons to set up confining potentials



"Linear confinement"

(From Lattice & Hadron Spectroscopy)



Map to Strings: Quarks ➡ string endpoints; gluons ➡ "kinks"

System then evolves as a string world sheet

+ **String breaks** via spontaneous $q\bar{q}$ pair creation ("Schwinger mechanism") → **hadrons**

Baseline string model formulated in continuum limit of asymptotically "long" strings: $E_{\rm CM} \gtrsim 10\,{\rm GeV}$

Belle II could provide **extremely accurate constraints** at the lower endpoint of the dynamical range?

+ test for **small-system modifications** ⟷ eg non-universal best-fit tune parameters

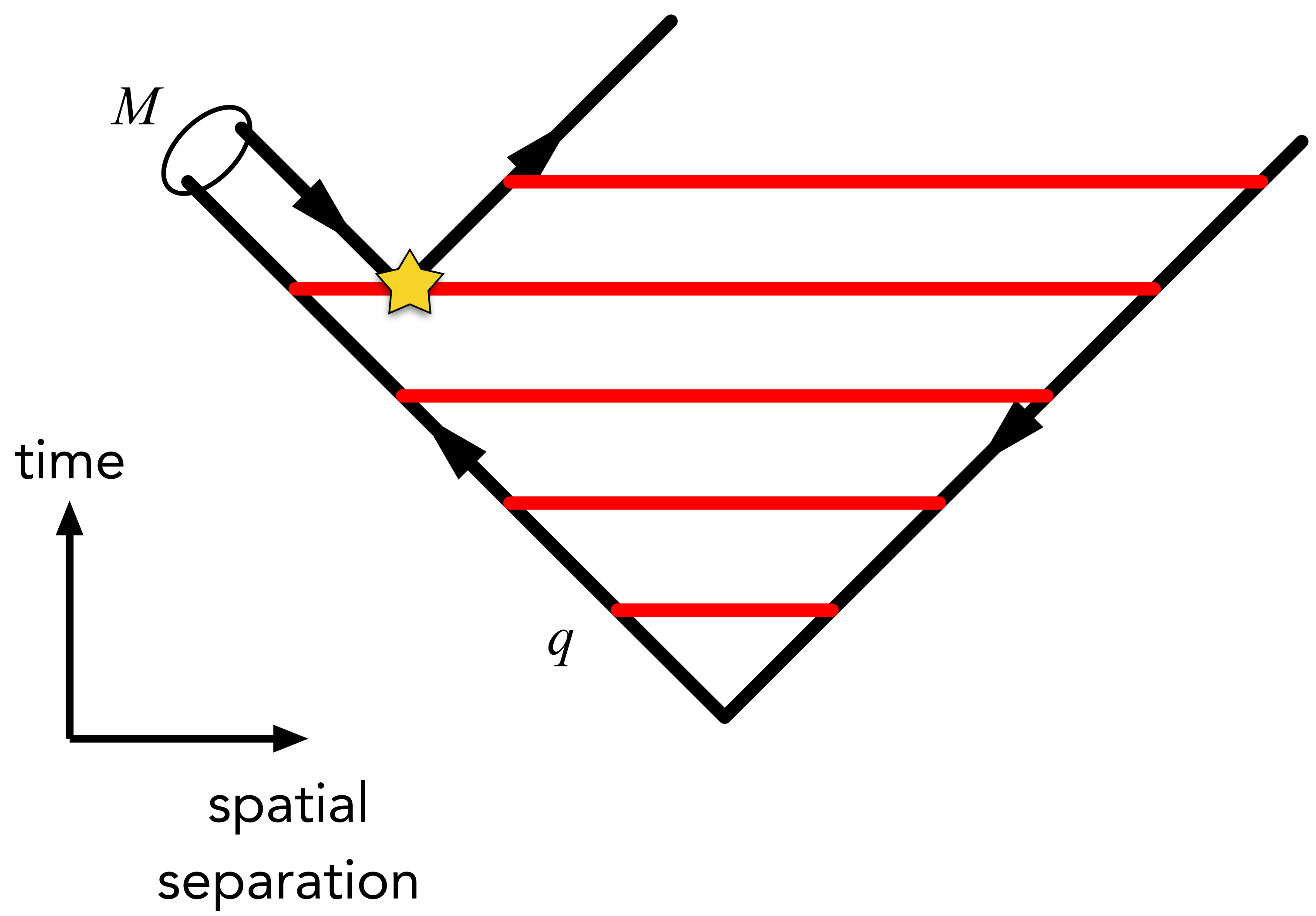
String **Breaking**

In "unquenched" QCD

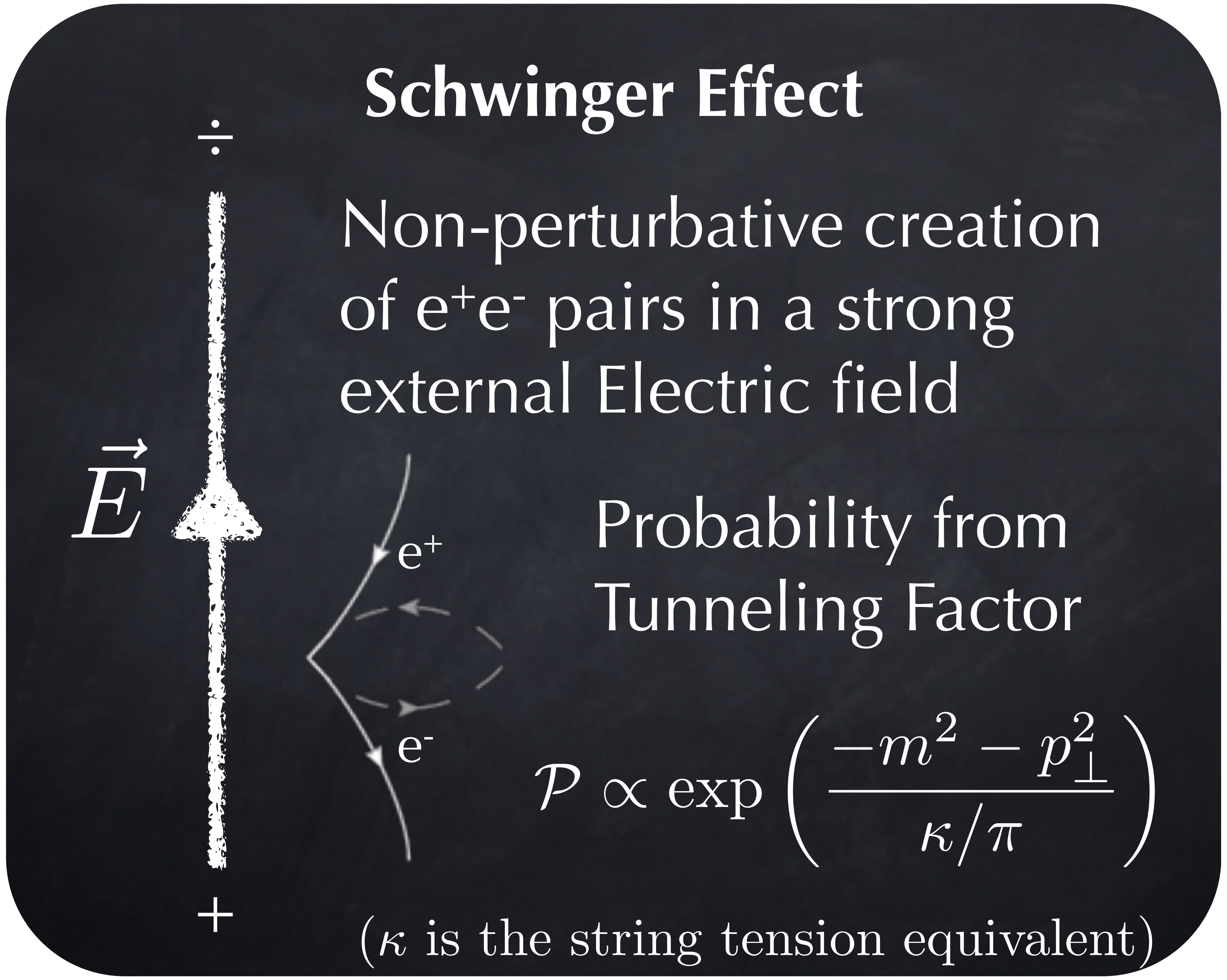
$g \to q\bar{q} \implies$ The strings will "break"

Non-perturbative so can't use $P_{g\to q\bar{q}}(z)$

Model: Schwinger mechanism →



J. Schwinger, Phys. Rev. **82** (1951) 664



→ Gaussian suppression of high $m_\perp = \sqrt{m_q^2 + p_\perp^2}$

Assume probability of string break constant per unit world-sheet area

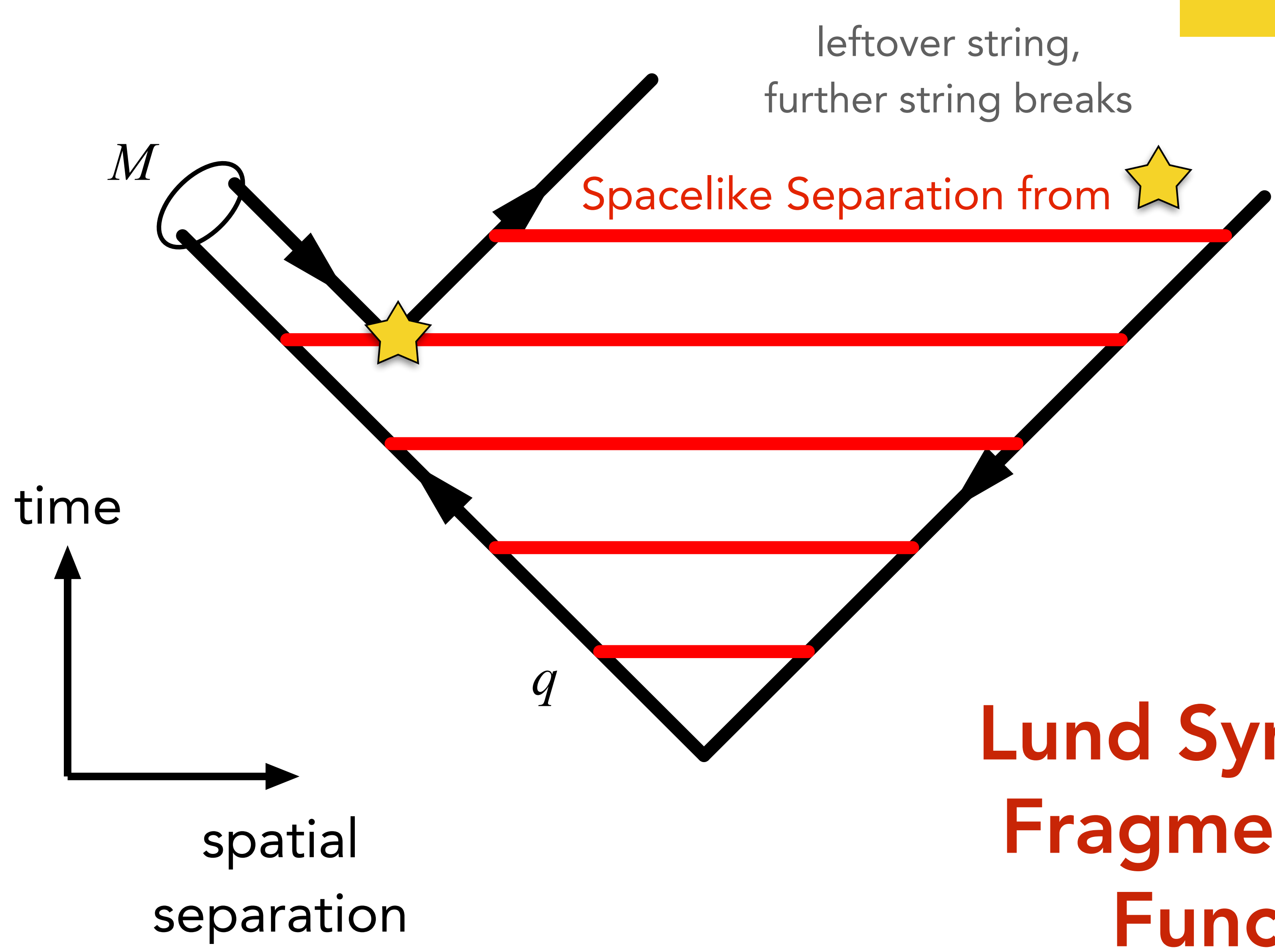
Schwinger Case: **the String Fragmentation Function**

Schwinger $\Longrightarrow$ Gaussian $p_\perp$ spectrum (transverse to string axis) **& Prob(d:u:s) ≈ 1 : 1 : 0.2**

The meson M takes a fraction z of the quark momentum,

Probability distribution in $z \in [0,1]$ parametrised by **Fragmentation Function**, $f(z, Q^2_{\mathrm{HAD}})$

Observation: All string breaks are **causally disconnected**



Lorentz invariance $\Longrightarrow$ string breaks can be considered in *any order*. Imposes "left-right symmetry" on the FF

$\Longrightarrow$ FF constrained to a form with **two free parameters**, a & b: constrained by fits to measured hadron spectra

Lund Symmetric Fragmentation Function

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Supresses high-z hadrons (↑ a)

Supresses low-z hadrons (↑ b)

Constraining PYTHIA (in the $q\bar{q}$ continuum)

We use a combination of Infrared Safe* and Infrared Sensitive observables

$\Longrightarrow$ Stereo Vision on perturbative and nonperturbative QCD respectively

Some overlap / interplay: IR Safe becomes Sensitive at low scales & IR Sensitive seeded by IR Safe.

IR Safe Observables satisfy two simultaneous conditions

1) Soft Safe: observable does not change when adding soft partons/particles

E.g., adding infinitely soft gluons (perturbative), or soft pions (non-perturbative)

2) Collinear Safe: observable does not change when splitting a particle collinearly

E.g., doing a $g \to gg$ or $g \to q\bar{q}$ splitting, or a $\rho \to \pi\pi$ decay, in limit of zero opening angle.

➜ Hadronization and hadron decays suppressed by powers of $\Lambda_{\rm QCD}/Q$

Full Set of IR Safe Observables:

Event Shapes: typically Thrust Family, Linearised Sphericity Family, EECs, Angularities

Jet Rates: typically Durham kT resolutions (but other clustering algorithms also interesting)

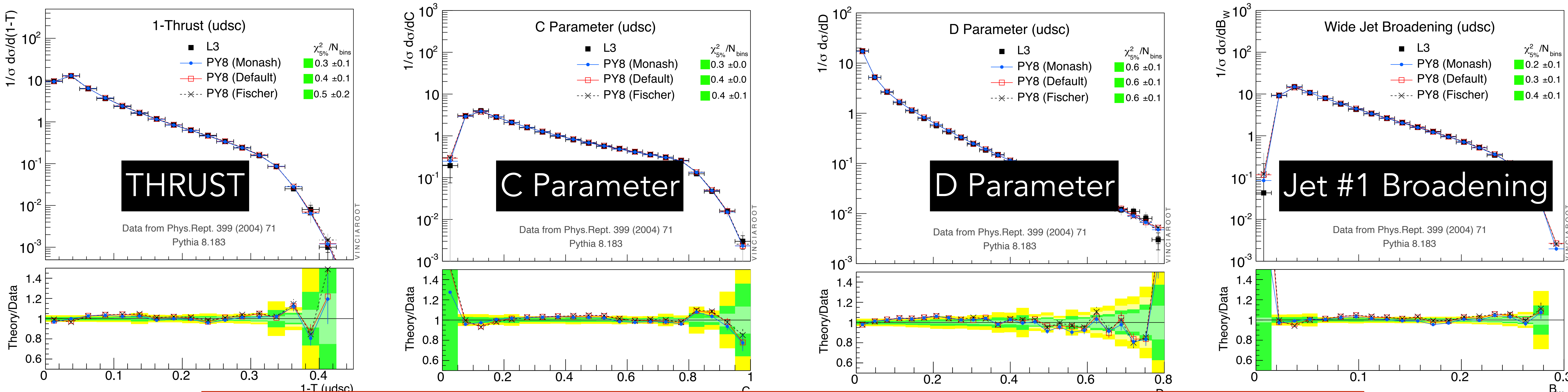
Jet Structure: Jet Masses, Jet Broadenings, Jet Shapes

Sometimes done using Charged Tracks only, for best experimental resolution.

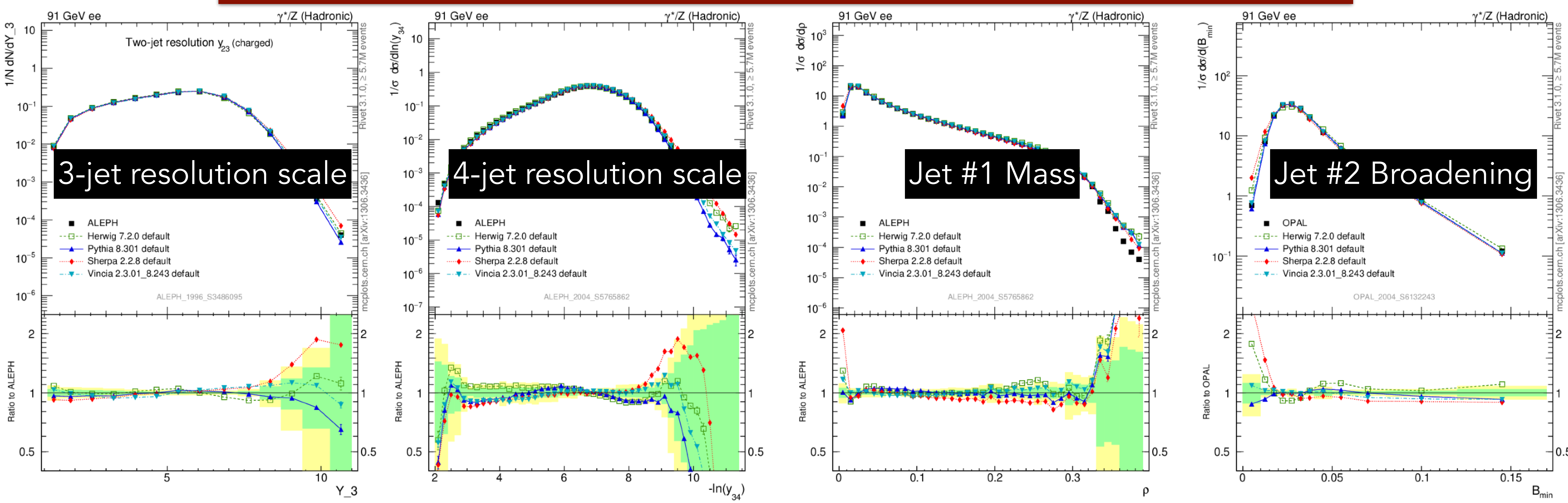
*Sometimes referred to as IRC safe

Constraining PYTHIA: **IR Safe Observables** (main examples) (at $\sqrt{s} \sim m_Z$)

Top Row: from PS et al., "Tuning PYTHIA 8.1: the Monash 2013 Tune", Eur.Phys.J.C 74 (2014) 8



Question: could Belle II separate $e^+e^- \to \gamma^* \to c\bar{c}$ out from $d\bar{d}, u\bar{u}, s\bar{s}$?



Bottom Row: from mcplots.cern.ch

Multiplicities, Spectra, and Correlations

Inclusive charged particles

Identified particles (rates and ratios).

+ correlations, with event multiplicity, with rapidity along jet axis, with … ?

Strangeness correlations, baryon correlations, …

Spectra

Conventional absolute momentum fraction: $x_p = \frac{2|p|}{E_{CM}}$

But, even at $E_{CM} \sim 10$ GeV, these hadrons are produced in **jets**;

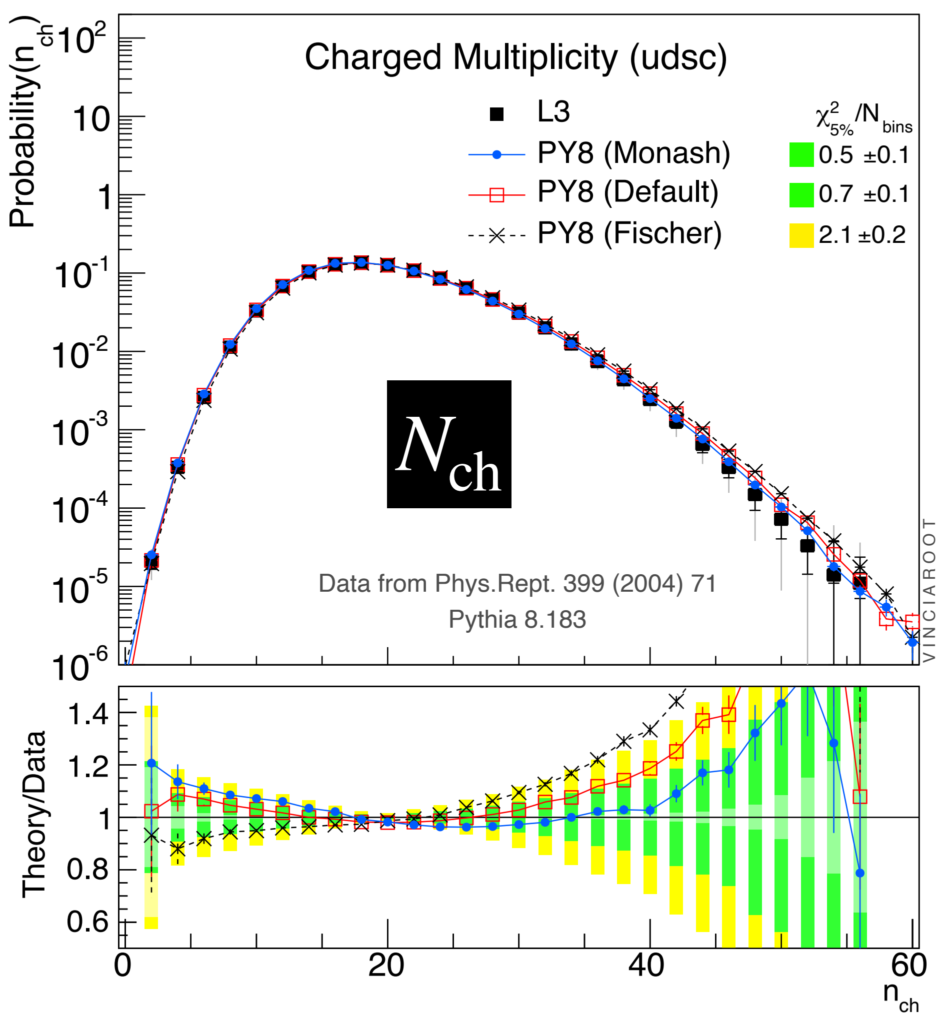
Jets have longitudinal and transverse axes:

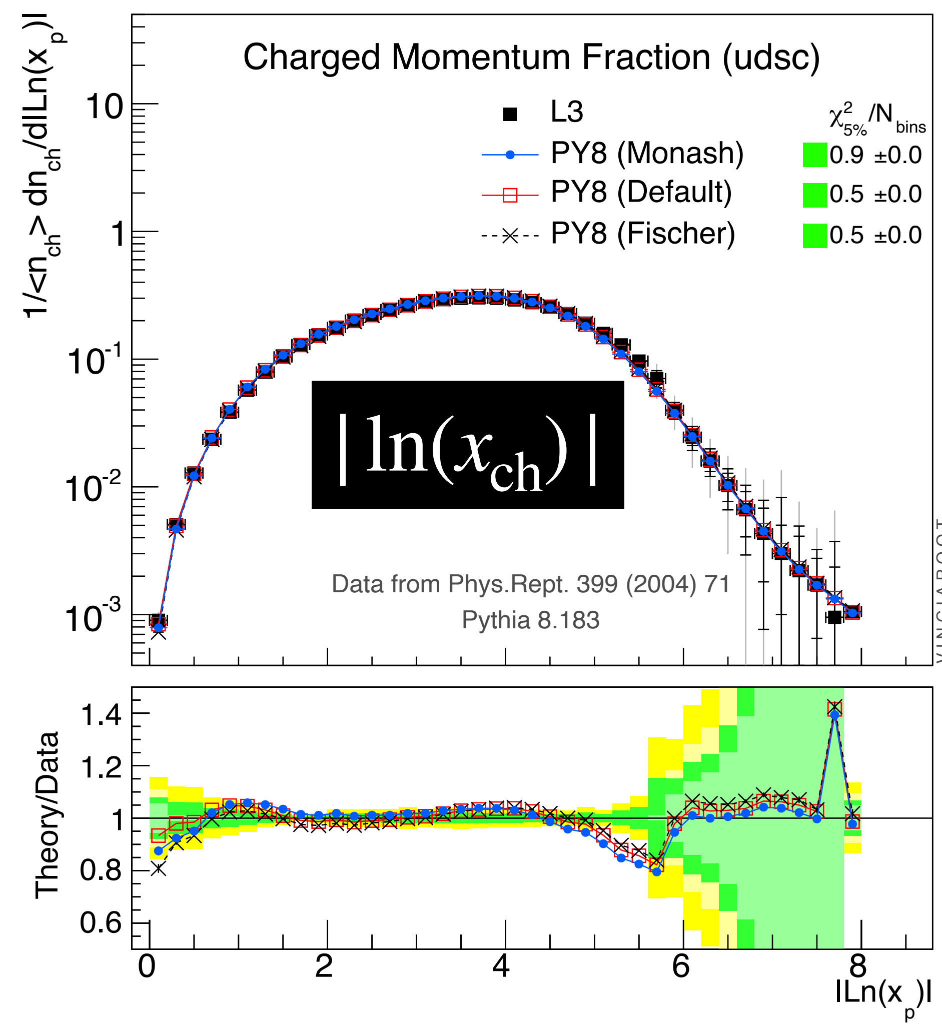
More information: rapidity spectra (along primary event/jet axis) : dn_{ch}/dy, dn_{PID}/dy

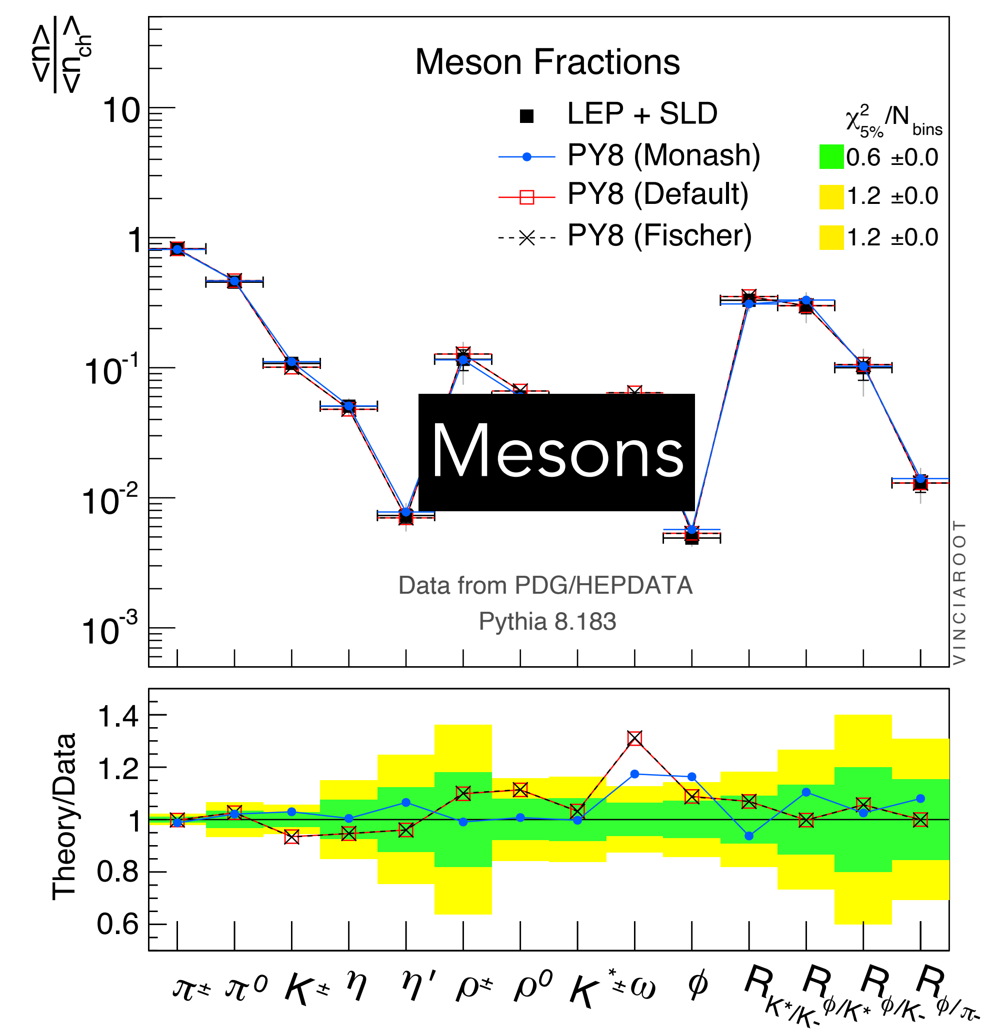
And momentum **transverse to it**, $d\mathrm{n}/dp_\perp$; + Let 2[nd] axis define a plane $\Longrightarrow p_{\perp in}, p_{\perp out}$

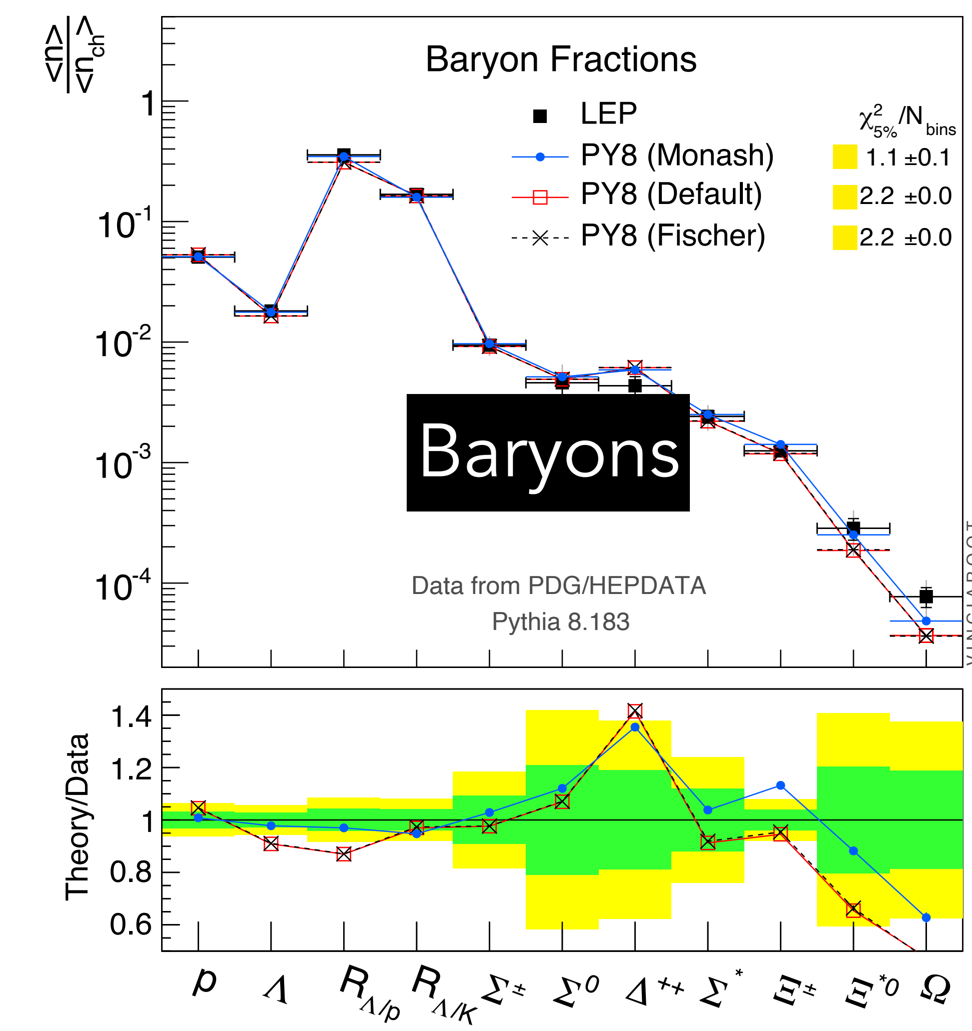
Main Examples of IR Sensitive Observables (at $\sqrt{s} \sim m_Z$)

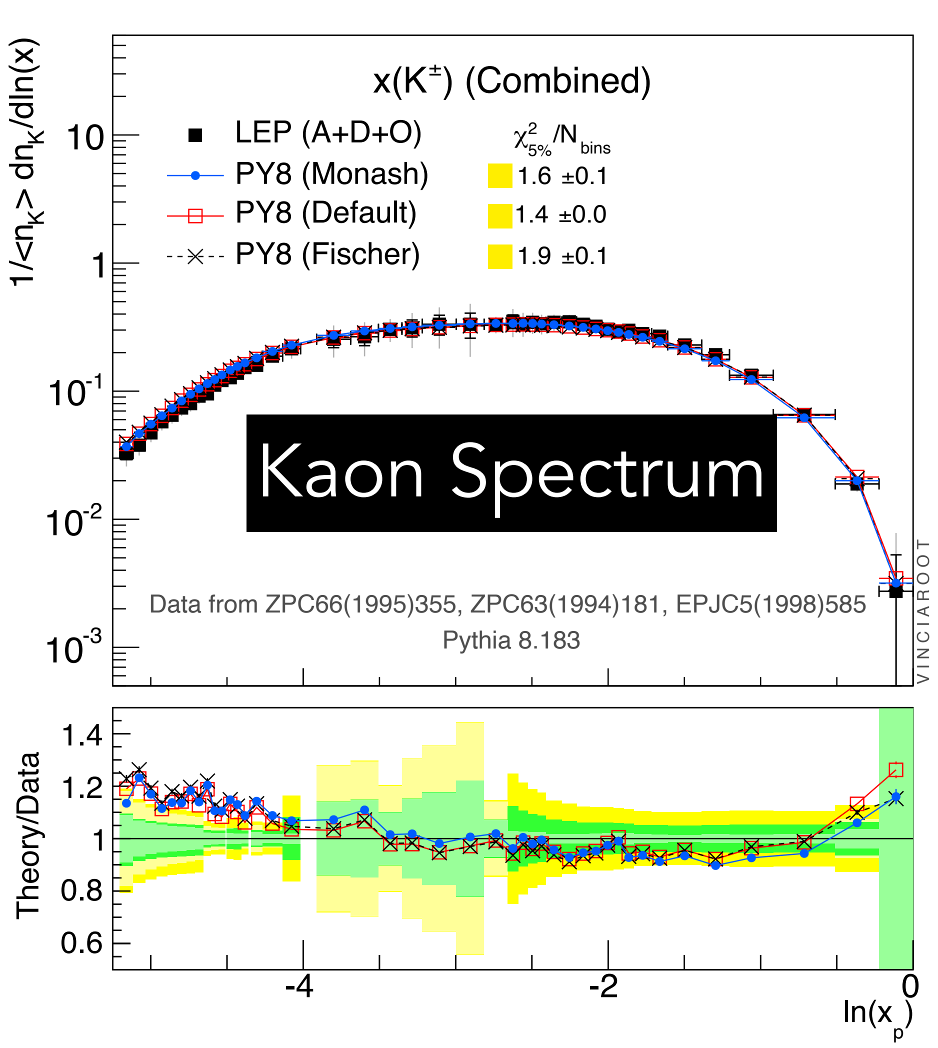
Top Row: from PS et al., “Tuning PYTHIA 8.1: the Monash 2013 Tune”, Eur.Phys.J.C 74 (2014) 8

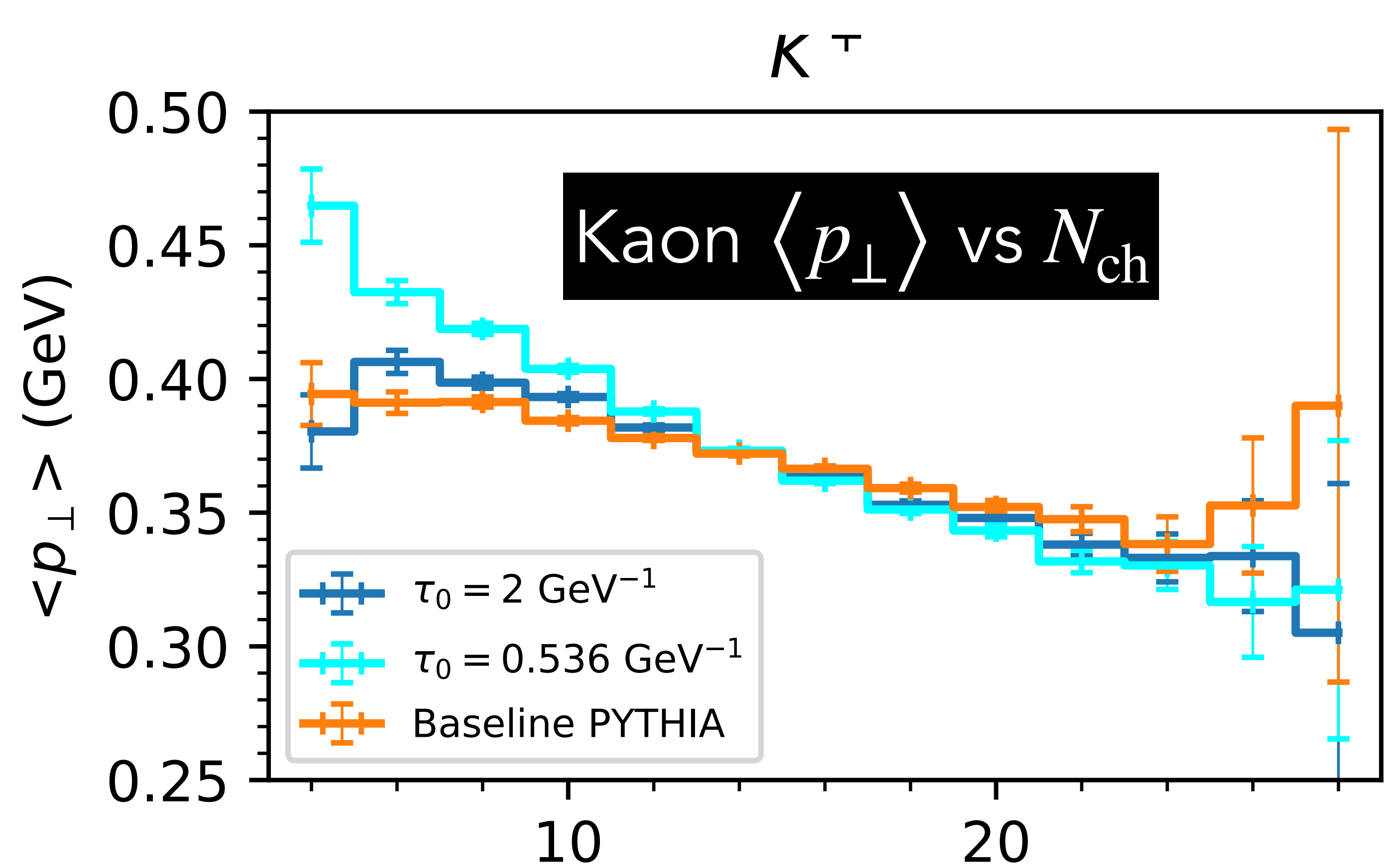


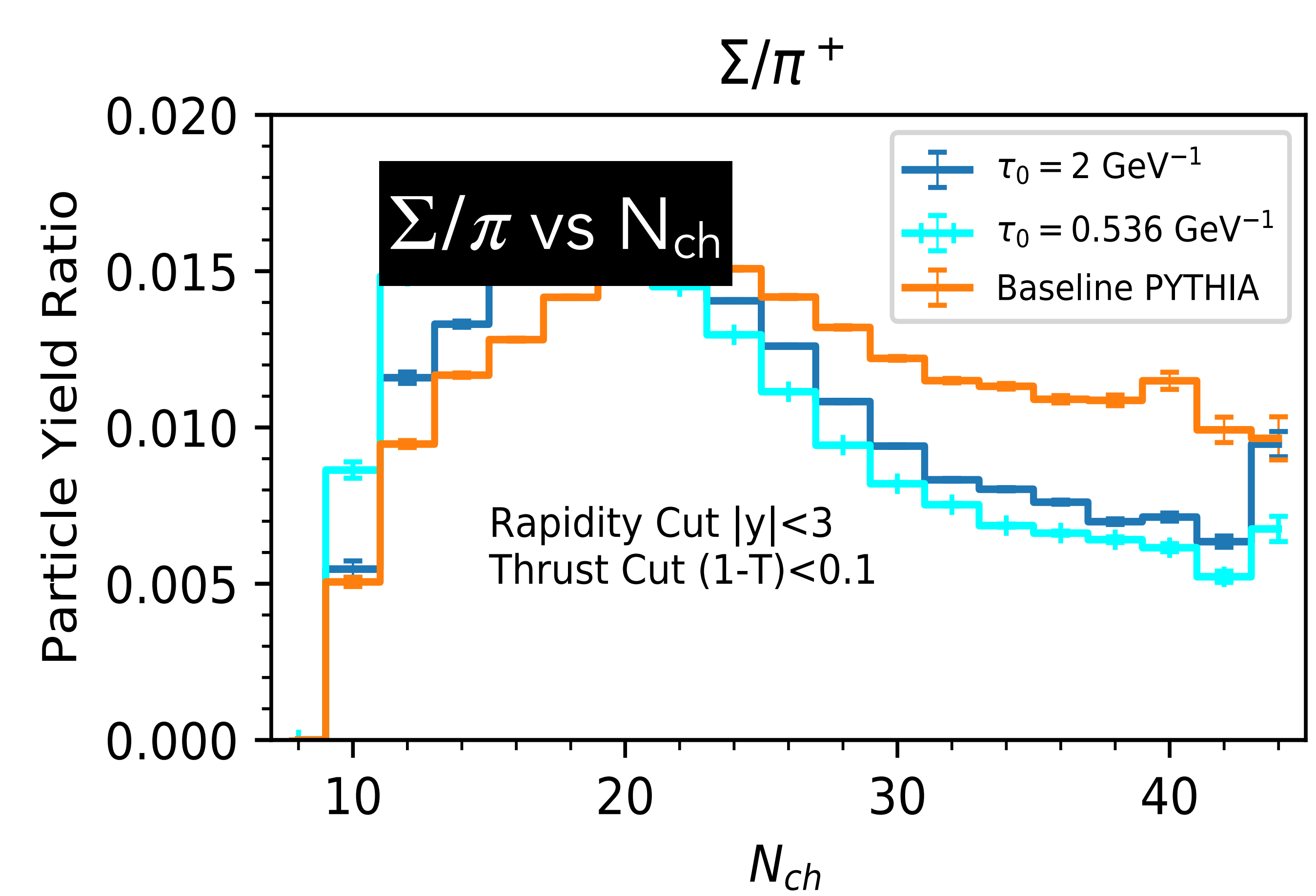












Bottom Right Plots: from “String Fragmentation with a Time-Dependent Tension”, N. Hunt-Smith & **PS**, Eur.Phys.J.C 80 (2020) 11

PYTHIA & B Decays — Recent collaboration with EVTGEN (M. Kreps, Warwick)

30% of B meson decays modelled as partonic transitions, with spectator

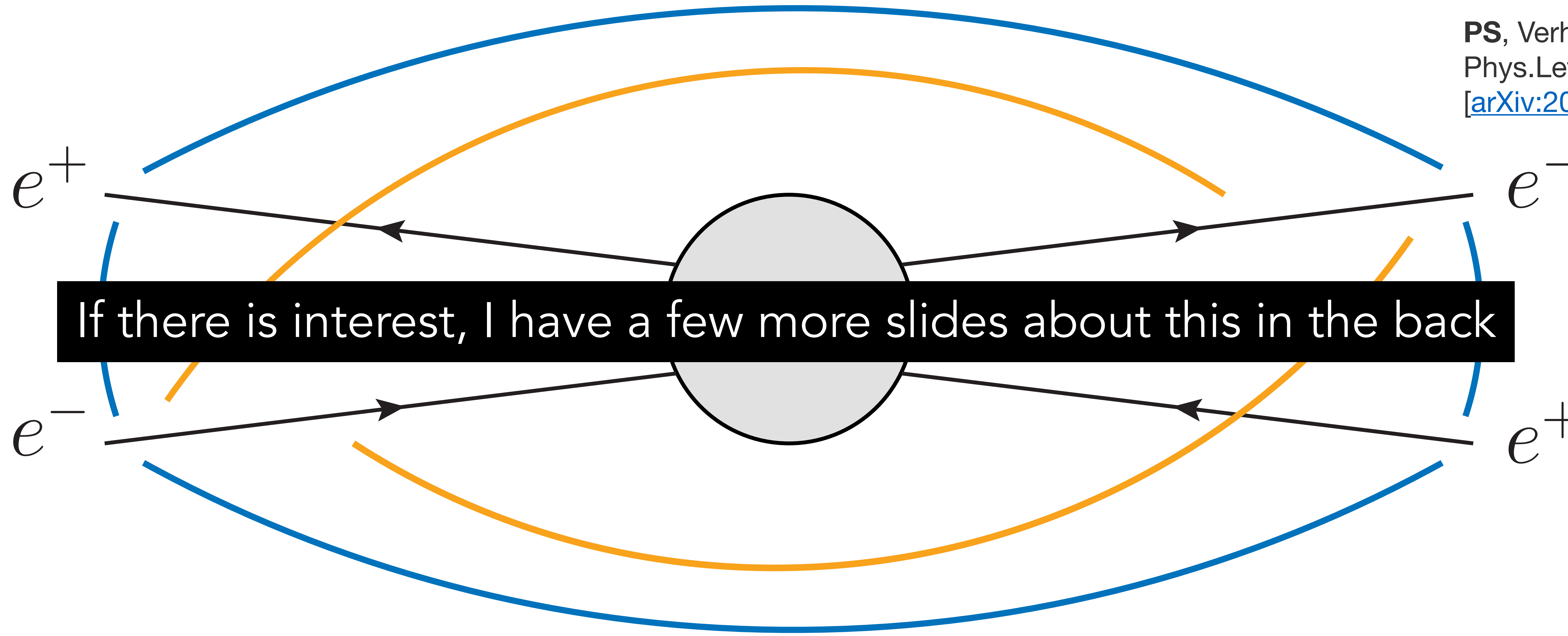
- Passed back to PYTHIA for re-hadronisation (with same string parameters as at LEP).
  - How reliable is this modelling really? Not aware anyone has looked at that since org papers.
- These tend to be high-multiplicity (multi-prong) modes
  - Rarely used as signals. But enter as backgrounds, and tagging modes?
- Experimental constraints on these? Belle II, LHCb, ALICE … ?
  - **Would like to discuss, if there is interest, what Belle II could do here?**

QED Radiative Corrections in B Decays

- HERWIG and SHERPA have dedicated modules, based on **"YFS" formalism**
- For PYTHIA, QED in hadron decays is normally done with **PHOTOS**
- **Now:** looking at adapting the **QED Multipole Shower Module from VINCIA**
  - Native C++ and built-in in PYTHIA → thread-safe and trivial to parallelise
  - May be superior to YFS in some ways + modern shower formalism ⟹ matching, merging, …
  - **Would this be interesting to Belle II ?**

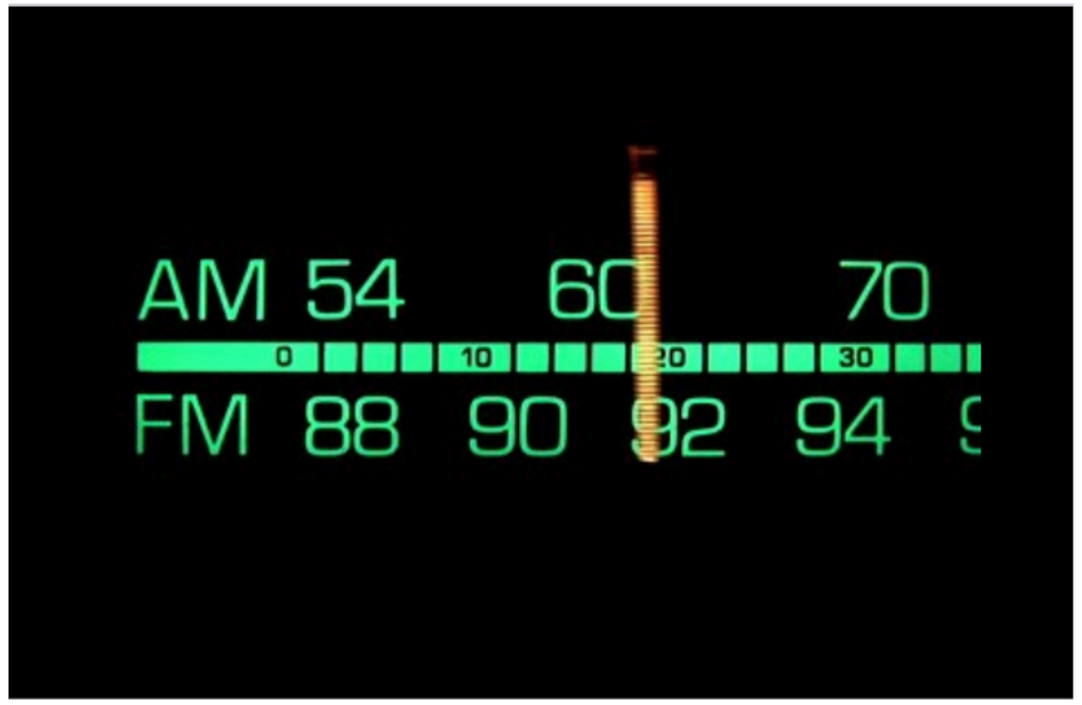
Example: Quadrupole final state (4-fermion: $e^+e^+e^-e^-$)

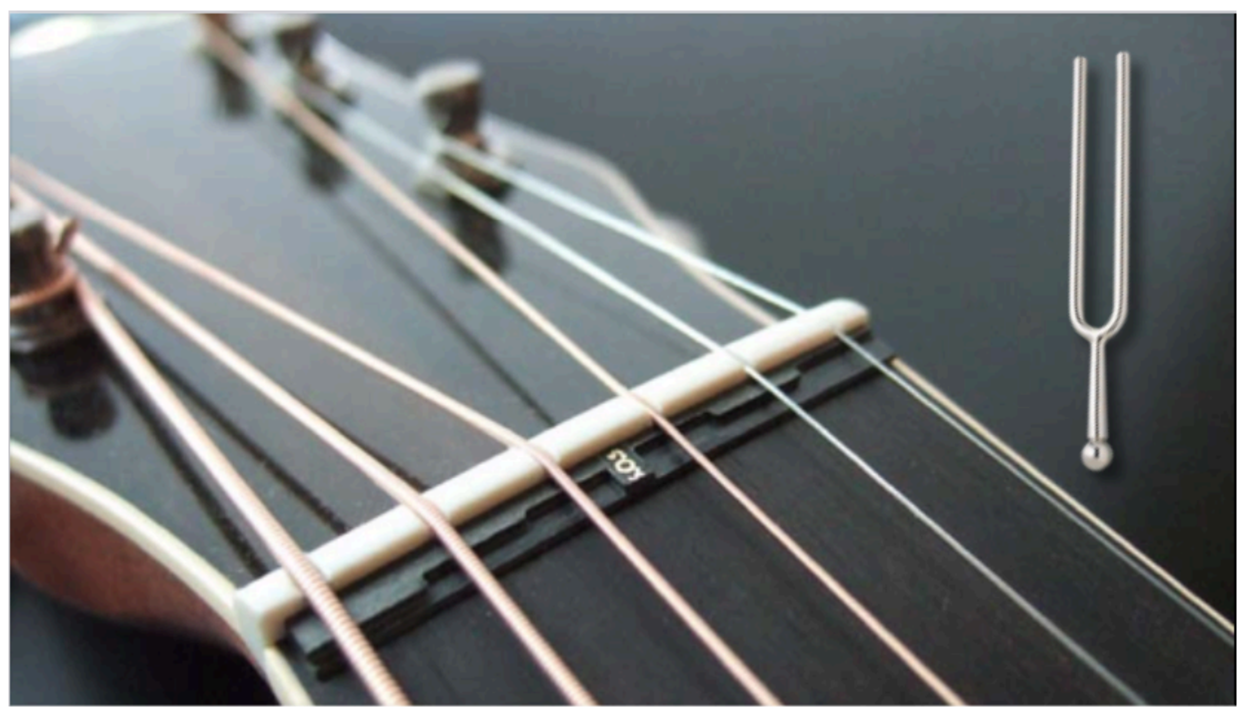
PS, Verheyen,
Phys.Lett.B 811 (2020) 135878
[arXiv:2002.04939]



Soft Photon Emission: $|M_{n+1}(\{p\},p_j)|^2 = -8\pi\alpha \sum_{x,y}^{n} \sigma_x Q_x \sigma_y Q_y \frac{s_{xy}}{s_{xj}s_{yj}} |M_n(\{p\})|^2$
[Dittmaier, 2000]

Opposite-charge pairs ➤ positive terms
Same-charge pairs ➤ negative terms





PART 2

Tuning

Tuning: PROFESSOR — a powerful tool for (semi)automated tuning

Inspired by idea pioneered by DELPHI (Hamacher et al., 1995):

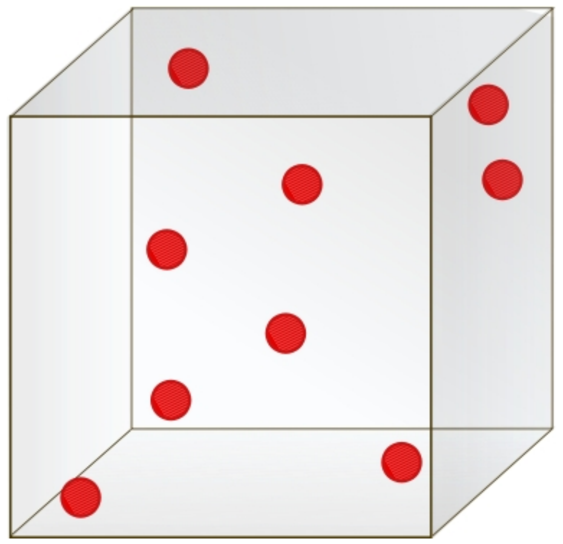
Bin-wise interpolation of MC generator response and χ^2 minimization

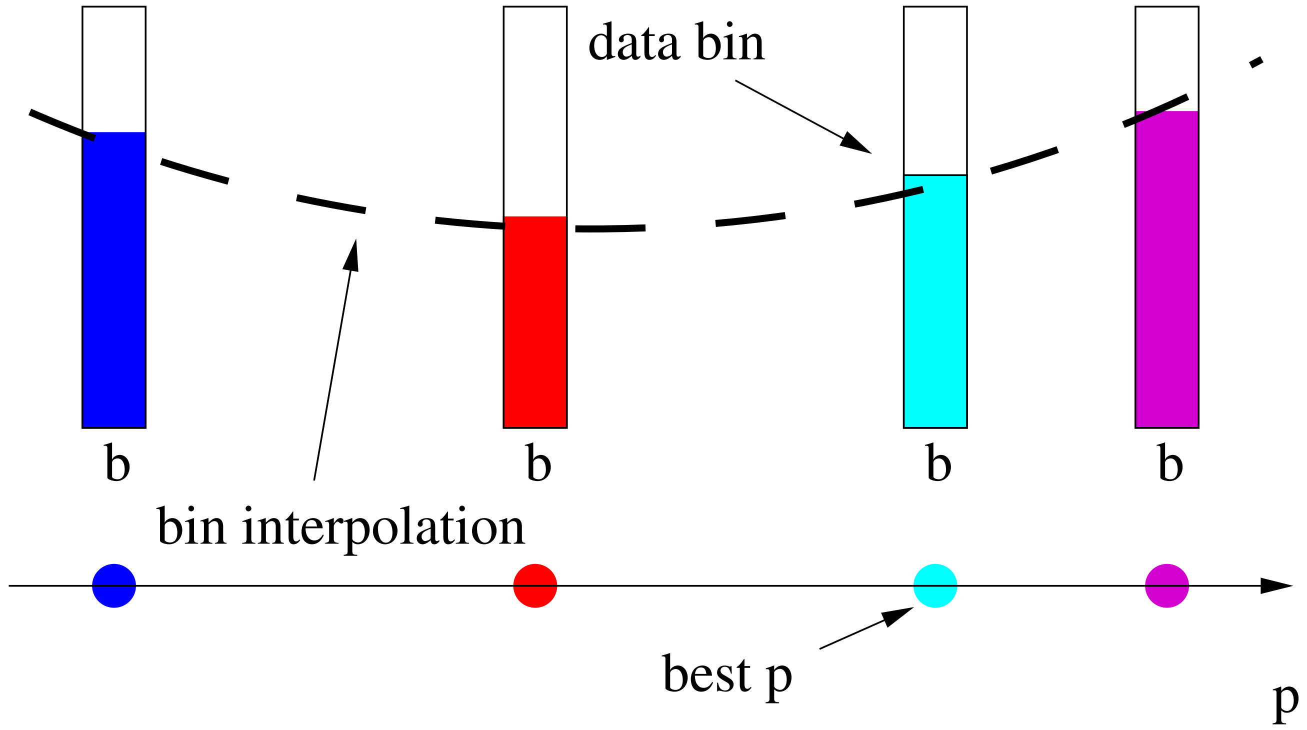
2^{nd}-order polynomials account for parameter correlations.

Modern Python Package with much more functionality, tutorials, etc.
https://professor.hepforge.org/

Professor
Tuning procedure

1. Random sampling: N parameter points in n-dimensional space
2. Run generator and fill histograms
3. For each bin: use N points to fit interpolation (2^{nd} or 3^{rd} order polynomial)
4. Construct overall (now trivial) $\chi^2 \approx \sum_{bins} \frac{(interpolation-data)^2}{error^2}$
5. and Numerically *minimize* `pyMinuit, SciPy`





PROFESSOR — Caveats

A. Buckley et al., *Eur.Phys.J.C* 65 (2010) 331 https://professor.hepforge.org/

I would (by now) recommend using PROFESSOR. Wisely.

Some Dangers:

Overfitting: very precisely measured data points can generate large χ^2 values even if MC gets within what one would naively consider "reasonable" agreement

- Fit reacts by sacrificing agreement elsewhere (typically in tails) to improve χ^2 in peaks.
- PROFESSOR now has facility to include a "sanity limit" (e.g., 5%) "theory uncertainty"
- ➤ Fit not rewarded (much) for improving agreement beyond that point. More freedom in tails.
- Also tends to produce $\chi^2_{5\%}$ values ~ unity → better uncertainty bands?

Incompatibilities: model may be ***unable*** to agree with (some part of) a given measurement

- Fit reacts by desperately trying to reduce order-of-magnitude differences in bins it shouldn't have been asked to fit in the first place, at cost of everything else ➤ total garbage.
- Choose measurements carefully — within domain of applicability of physics model
- \+ PROFESSOR now has facility to not penalise χ^2 beyond some max deviation.

Some Helper Tools

Wouldn't it be nice if there was a tool:

That could automatically detect correlations between parameters and observables.

And tell you which "groups" they fall into naturally : which parameter sets you should ideally tune together, and which are more nicely factorised.

This is (at least partly) **what the tool AutoTunes does** Bellm, Gellersen, Eur.Phys.J.C 80 (2020)

I won't have time to discuss that today, but I think it looks promising

I encourage you to study it and use it

You may also be interested in Apprentice Krishnamoorthy et al., EPJ Web Conf. 251 (2021) 03060

Variance reduction to semi-automate how to weight observables & bins

Practical Example: Uncertainties on Dark-Matter Annihilation Spectra

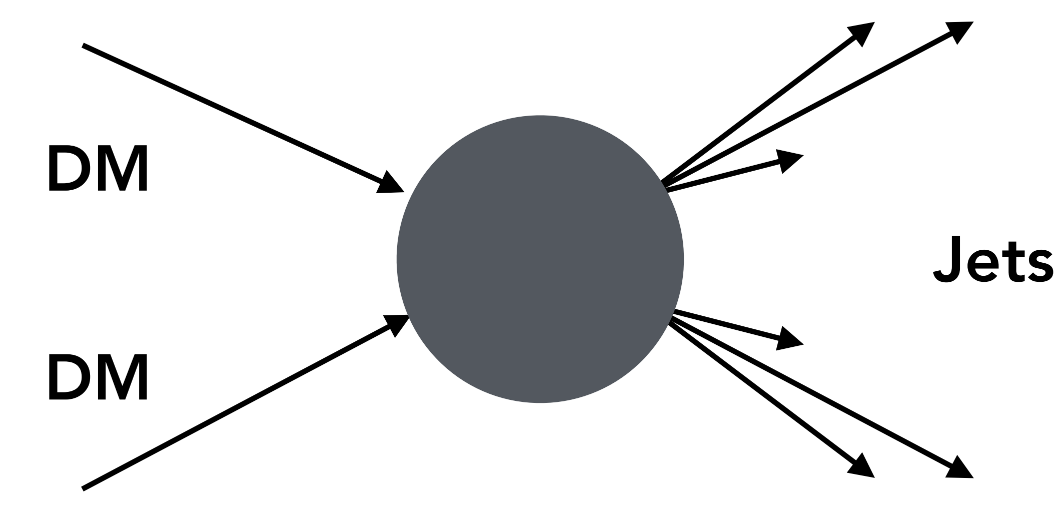
Based on A. Jueid et al., 1812.07424 (gamma rays, *eg for GCE*) and 2202.11546 (antiprotons, *eg for AMS*) + **2303.11363 (all)**

Compare different generators?

E.g., HERWIG – PYTHIA

Problem: tuned to ~ same data

Difference not guaranteed to span genuine uncertainties



Instead, did parametric refittings of LEP data within PYTHIA's modelling

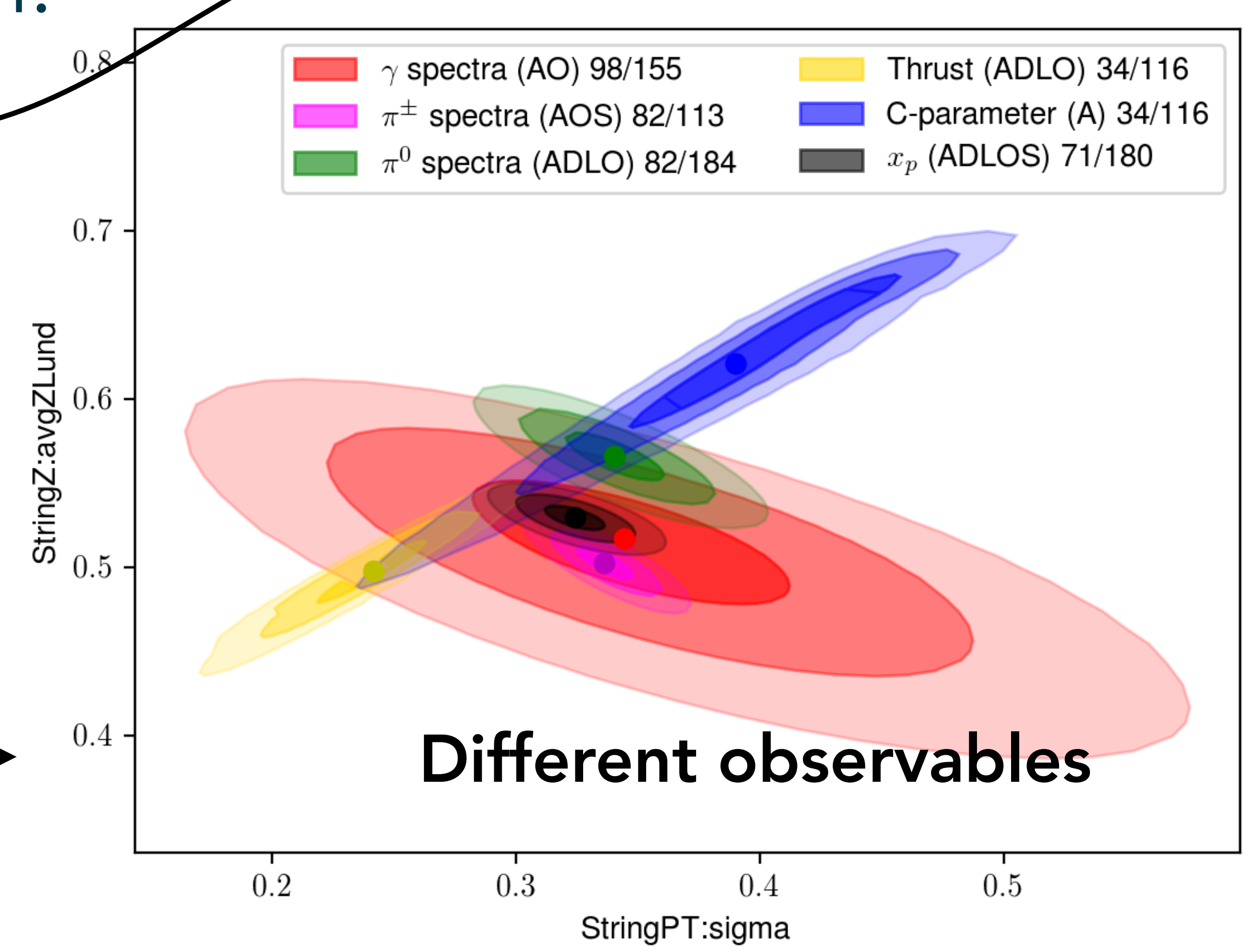
Simple sanity limit / overfit protection / tension resolution:

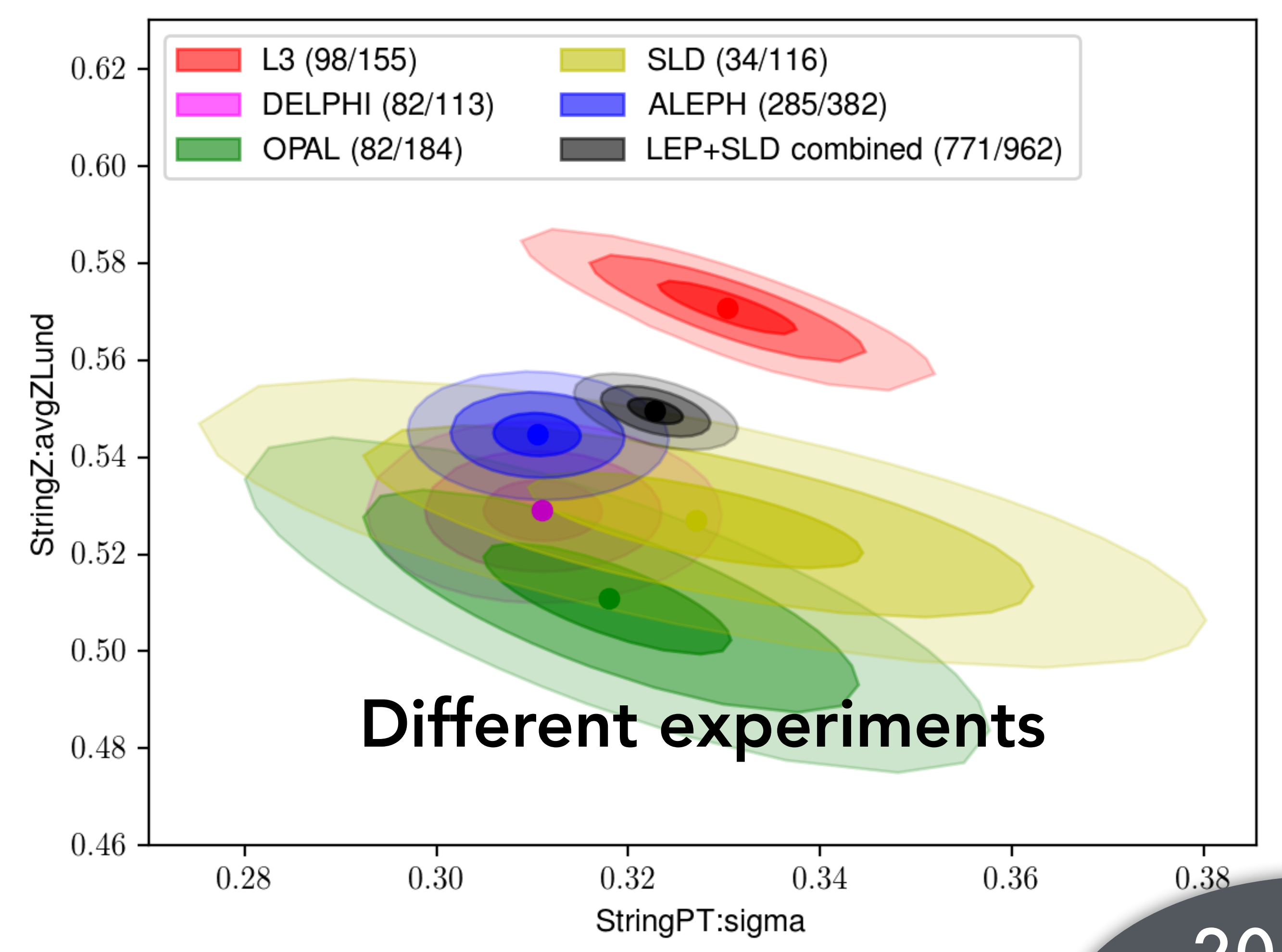
Add blanket 5% baseline uncertainty

(+ exclude superseded measurements)

Parameter	without 5%	with 5%
StringPT:Sigma	$0.3151^{+0.0010}_{-0.00010}$	$0.3227^{+0.0028}_{-0.0028}$
StringZ:aLund	$1.028^{+0.031}_{-0.031}$	$0.976^{+0.054}_{-0.052}$
StringZ:avgZLund	$0.5534^{+0.0010}_{-0.0010}$	$0.5496^{+0.0026}_{-0.0026}$
χ^2/ndf	5169/963	778/963

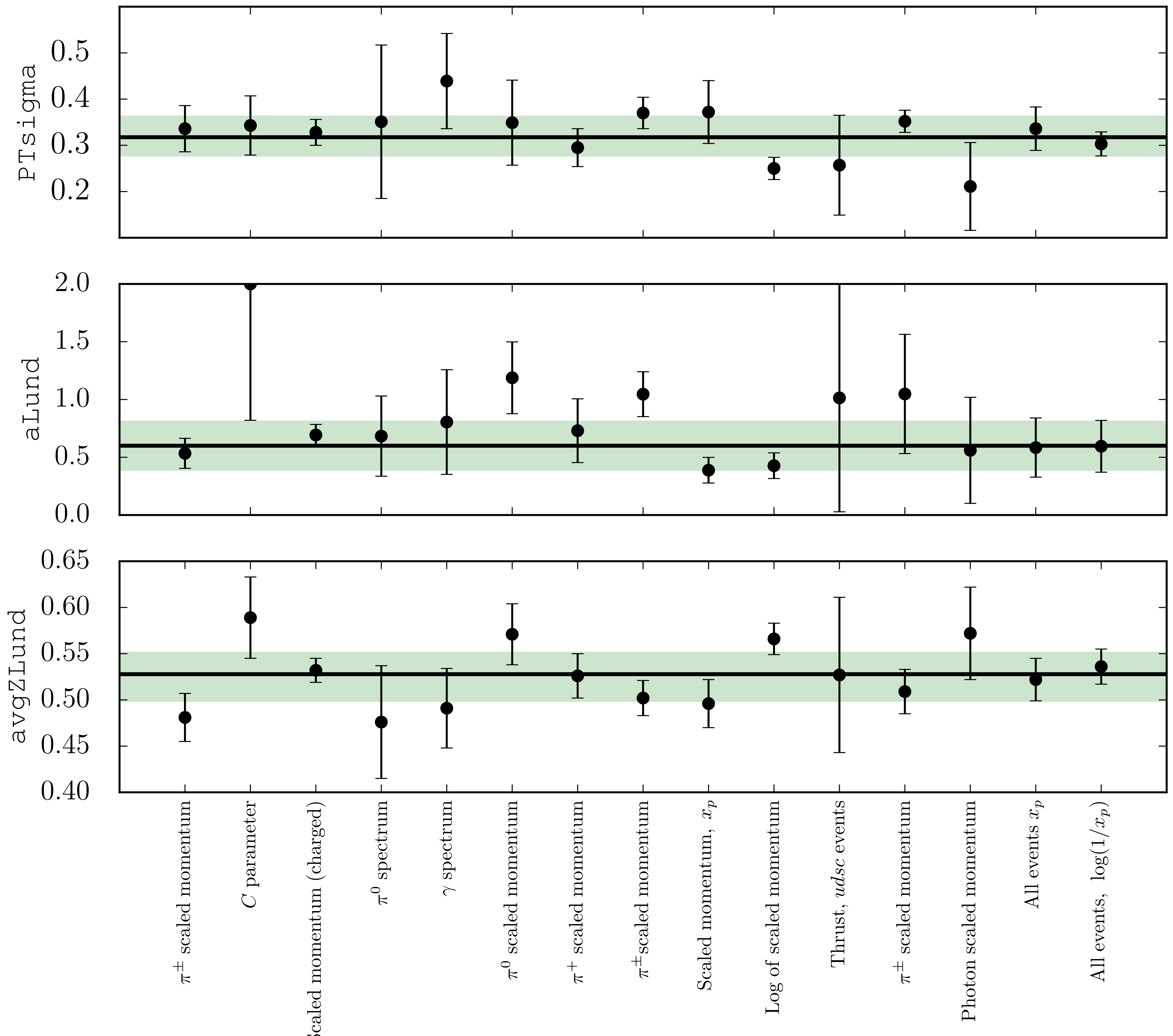
+ Universality Tests:





Practical Example: Uncertainties on Dark-Matter Annihilation Spectra

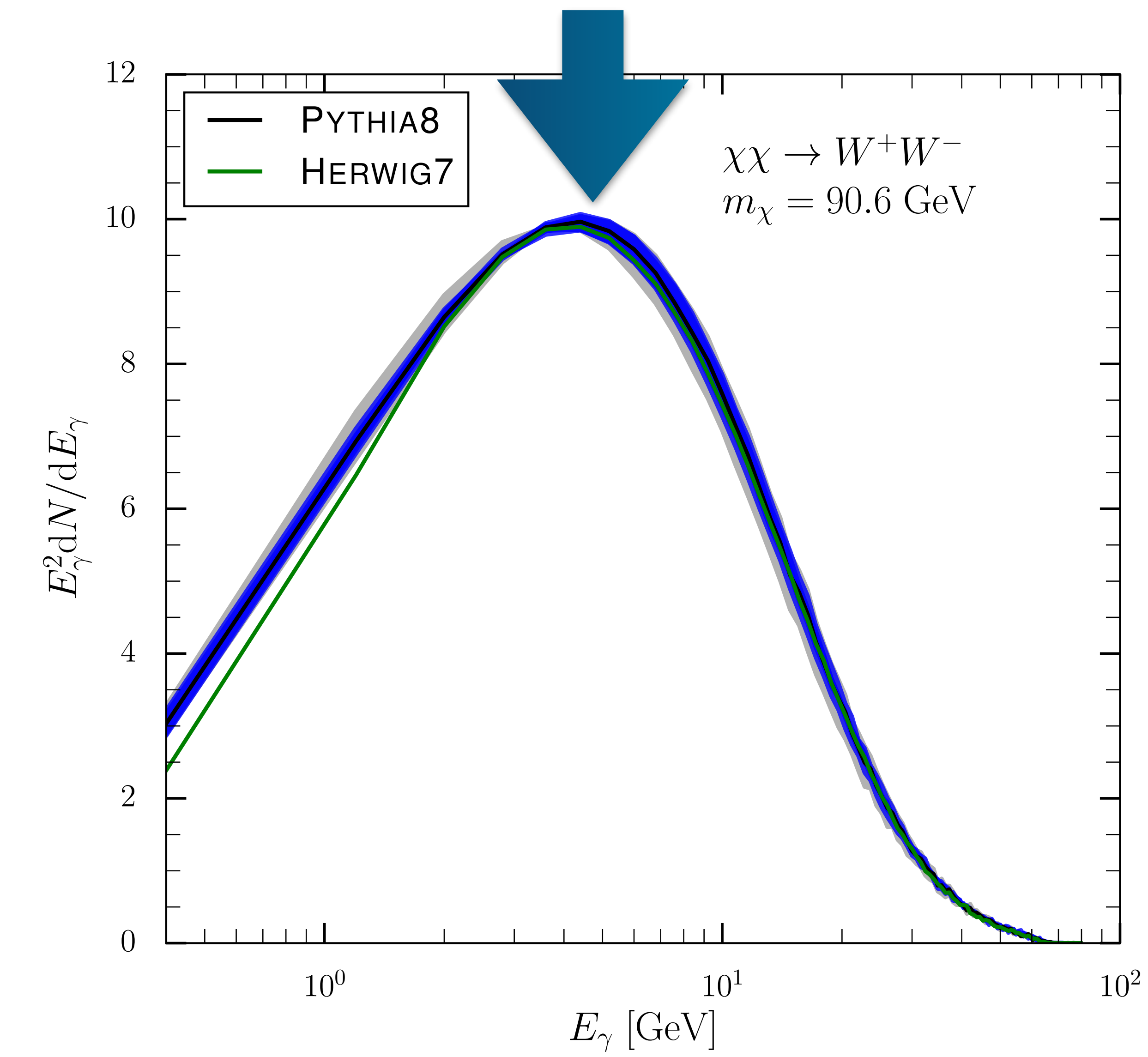
Based on A. Jueid et al., 1812.07424 (gamma rays, *eg for GCE*) and 2202.11546 (antiprotons, *eg for AMS*) + **2303.11363 (all)**



Weighted Average: good consistency across observables

Expensive?

10-point variations ➤ **Fairly convincing** uncertainty bands?



Same done for antiprotons, positrons, antineutrinos

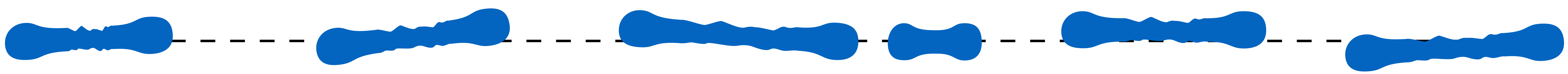
Main Contact: adil.jueid@gmail.com

Tables with uncertainties available on request. Also the spanning tune parameters of course.

New: Automated Hadronization Uncertainties

Problem:

Given a colour-singlet system that (randomly) broke up into a specific set of hadrons:



What is the **relative probability** that same system would have resulted, if the fragmentation parameters had been **different?**

Would this particular final state become **more likely** $(w' > 1)$? Or **less likely** $(w' < 1)$

Crucially: **maintaining unitarity** $\Longrightarrow$ inclusive cross section remains unchanged!

August 2023: Bierlich, Ilten, Menzo, Mrenna, Szewc, Wilkinson, Youssef, Zupan

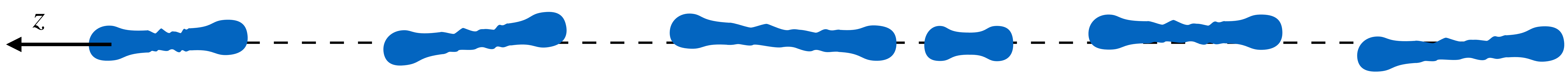
[*Reweighting MC Predictions & Automated Fragmentation Variations in Pythia 8*, 2308.13459]

Method is general; demonstrated on variations of the 7 main parameters governing longitudinal and transverse fragmentation functions in PYTHIA 8

https://gitlab.com/uchep/mlhad-weights-validation

[Reweighting MC Predictions & Automated Fragmentation Variations in Pythia 8, 2308.13459]

Longitudinal Fragmentation Function (Lund Symmetric FF)



$f(z)$ ~ ***scaled* light-cone hadron momentum fraction**

$$\propto \frac{1}{z^{1+r_Q b m_Q^2}} (1-z)^a \exp\left(-\frac{b m_\perp^2}{z}\right)$$

variations

Reweighting Methodology:

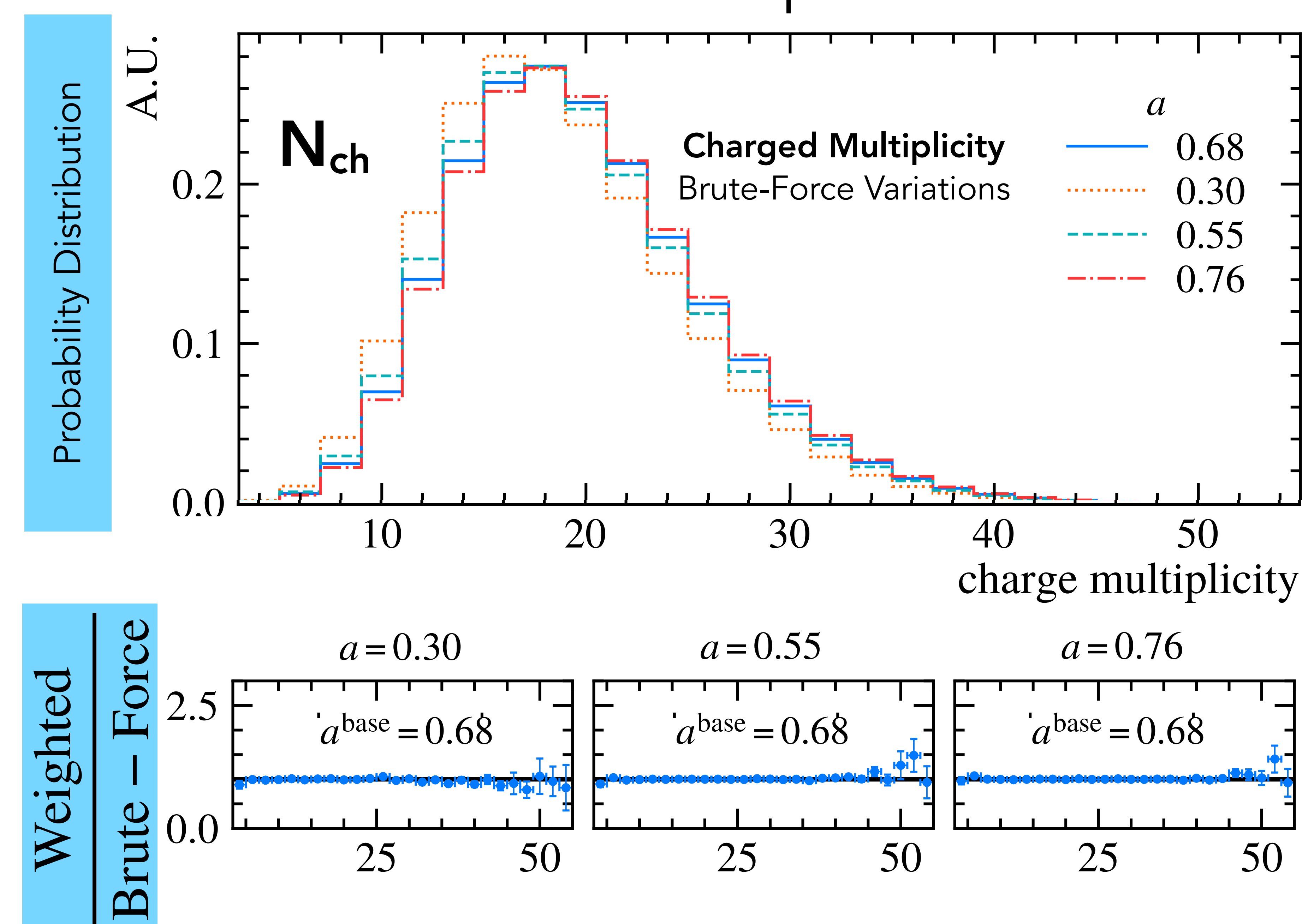
Accept-Reject Algorithm (analogous to shower variations):

$$w' = w \prod_{i \in \text{accepted}} R'_{i,\text{accept}}(z) \prod_{j \in \text{rejected}} R'_{j,\text{reject}}(z),$$

with

$$R'_{\text{accept}}(z) = \frac{P'_{\text{accept}}(z)}{P_{\text{accept}}(z)} \qquad R'_{\text{reject}}(z) = \frac{P'_{\text{reject}}(z)}{P_{\text{reject}}(z)} = \frac{1-P'_{\text{accept}}(z)}{1-P_{\text{accept}}(z)}$$

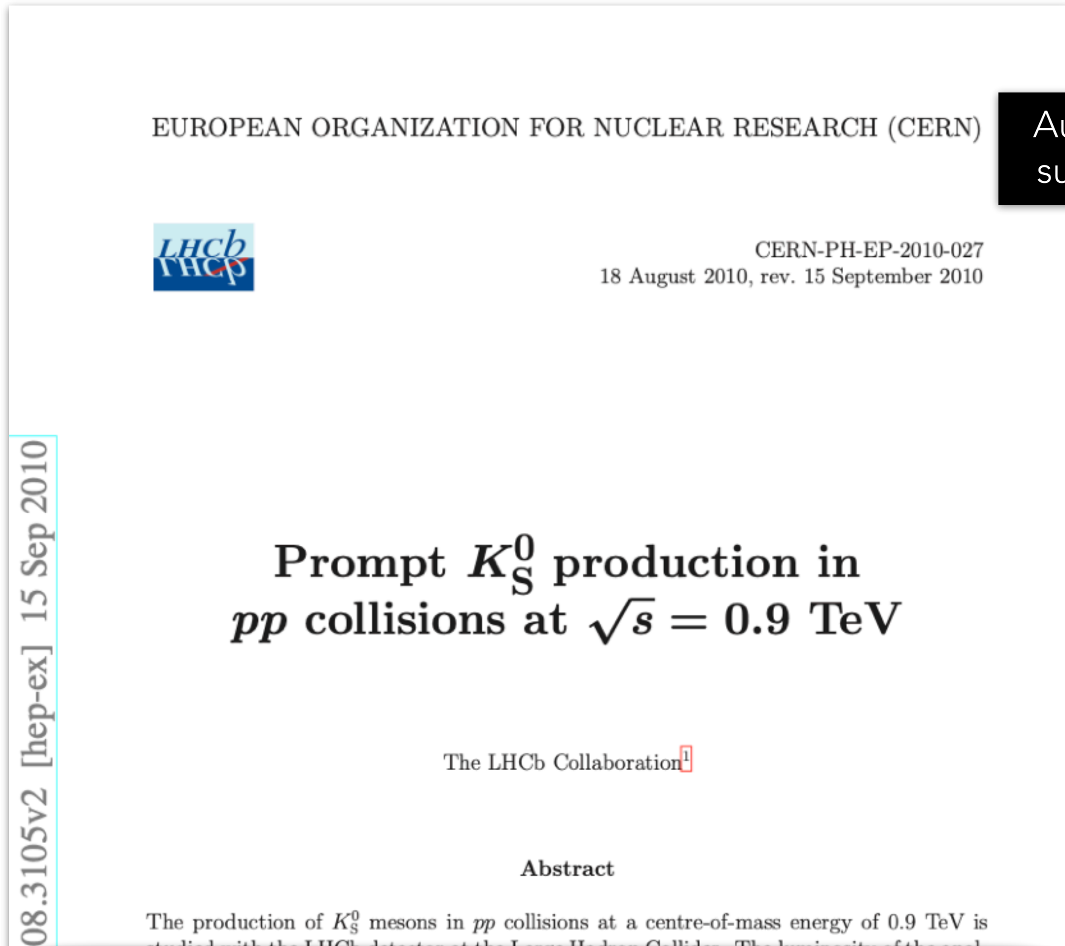
Example



(+ can vary 5 other parameters, in addition to a)

From Data Analysis ➠ Validation of (current & future) MC Event Generators

Experimental Measurement



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2010-027
18 August 2010, rev. 15 September 2010

arXiv:1008.3105v2 [hep-ex] 15 Sep 2010

Prompt K^0_S production in pp collisions at $\sqrt{s} = 0.9$ TeV

The LHCb Collaboration

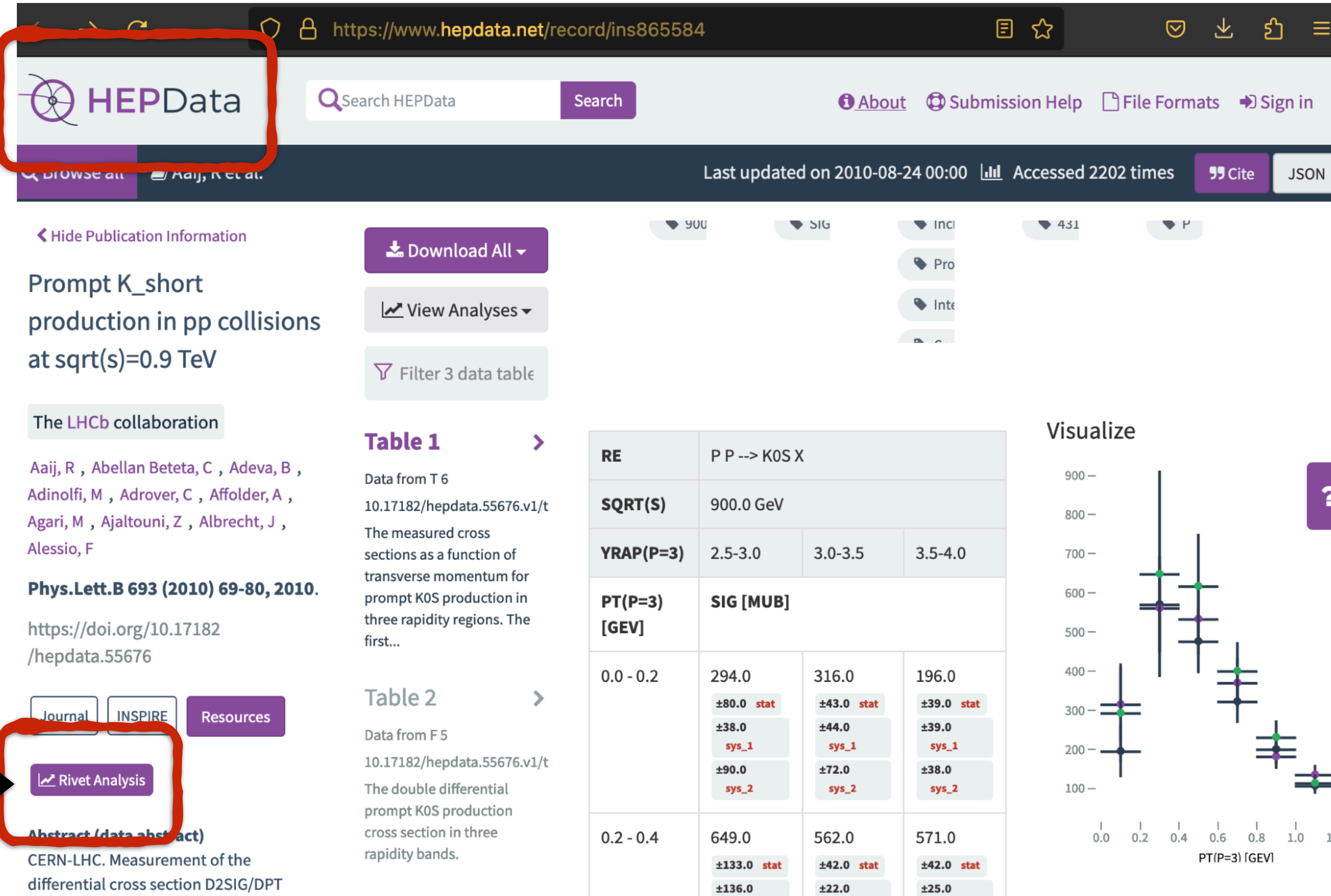
Abstract

The production of K^0_S mesons in pp collisions at a centre-of-mass energy of 0.9 TeV is

Authors prepare & submit records to:

Data Preservation (for HEP): **HEPData**

(HEPData is funded by the UK STFC and is based at the IPPP at Durham U.)



How to compare (unambiguously and exactly) to event generators?

(e.g., to validate future ones)

Need **Analysis Preservation** too

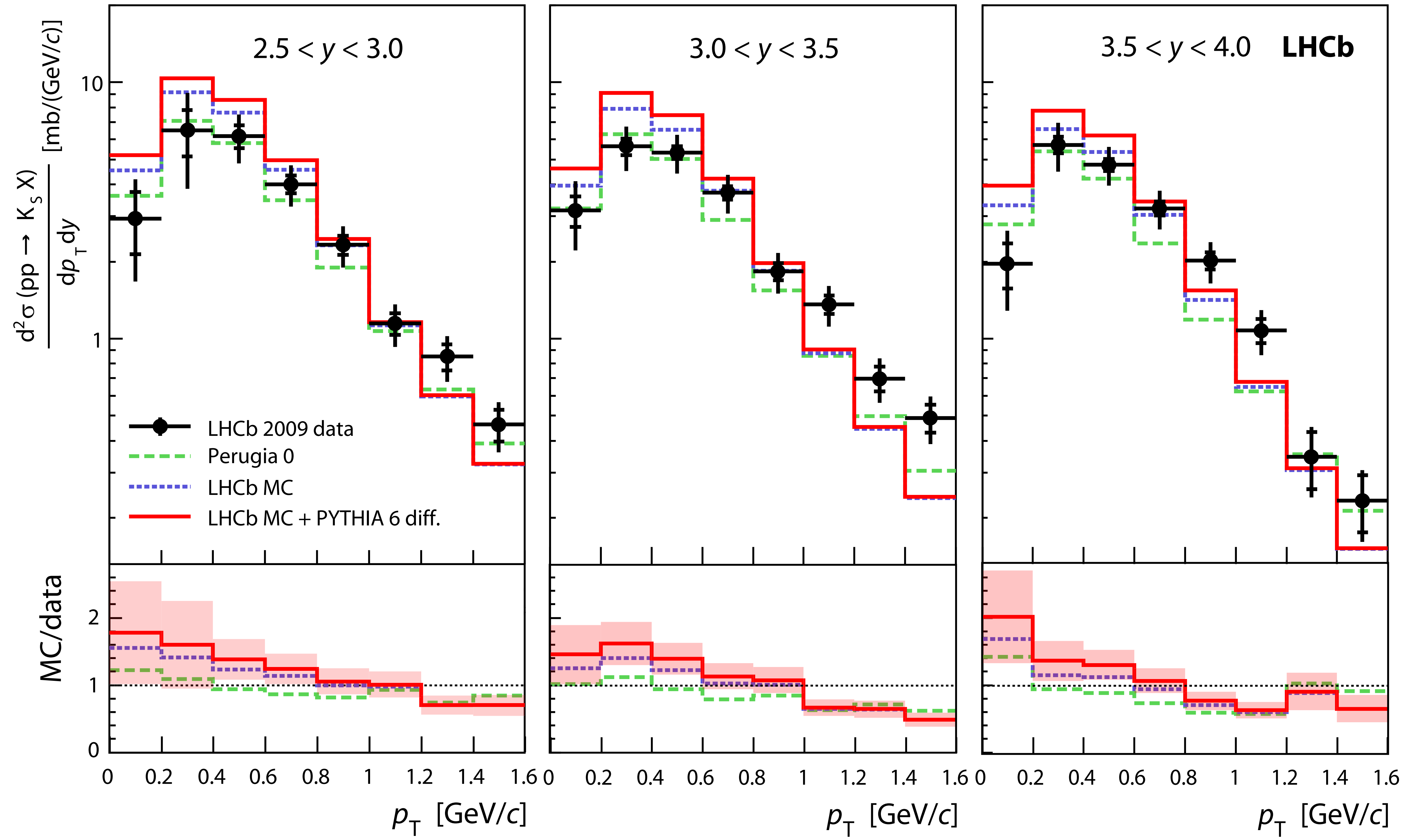
Authors prepare & submit **code** to:

Analysis Preservation (for HEP): **Rivet**

(Rivet is developed by the CEDAR project, also based in the UK)

When showing plots from **the original paper:**

Example:
Some kaon spectra
compared to MCs



"Yes but this has been corrected in version X of that generator"

"But this other tune or MC that you didn't compare to does better"

*"Does the model shown there also describe correctly this **other** important observable?"*

…

Instant answers would be convenient for faster & better informed discussions!

LHC@home/Test4Theory

2010: LHC@home developers approached the CERN Theory Group

Could we propose a simple test application for embedding physics applications in a Virtual Machine (CernVM) for running on the LHC@home volunteer cloud?

PYTHIA: simple to build (no external libs), small footprint, …

Would not previously have been able to run on a volunteer-cloud environment:

- No native Windows support, nor much interest (or manpower) to develop that
- Small group of physicists; main (only) goal (& grant funding) = physics research

Virtualisation factorised the problem:

Physics application just saw a (configurable) standard Linux environment (now CentOS)

Became the Test4Theory project, the world's first virtual volunteer cloud

Run event generators → RIVET and display results at mcplots.cern.ch

MCPLOTS — New Look Coming Soon

Work in Progress: A. Korneeva, A. Karneyeu, **PS**

ABOUT | PLOTS | COMPARISON | LHC@HOME

Preview at mcplots-dev.cern.ch

MCPLOTS

Online repository of Monte Carlo plots compared to experimental data

113 data analyses

126 generators

783667 plots

MCPLOTS — New Look Coming Soon

Work in Progress: A. Korneeva, A. Karneyeu, **PS**

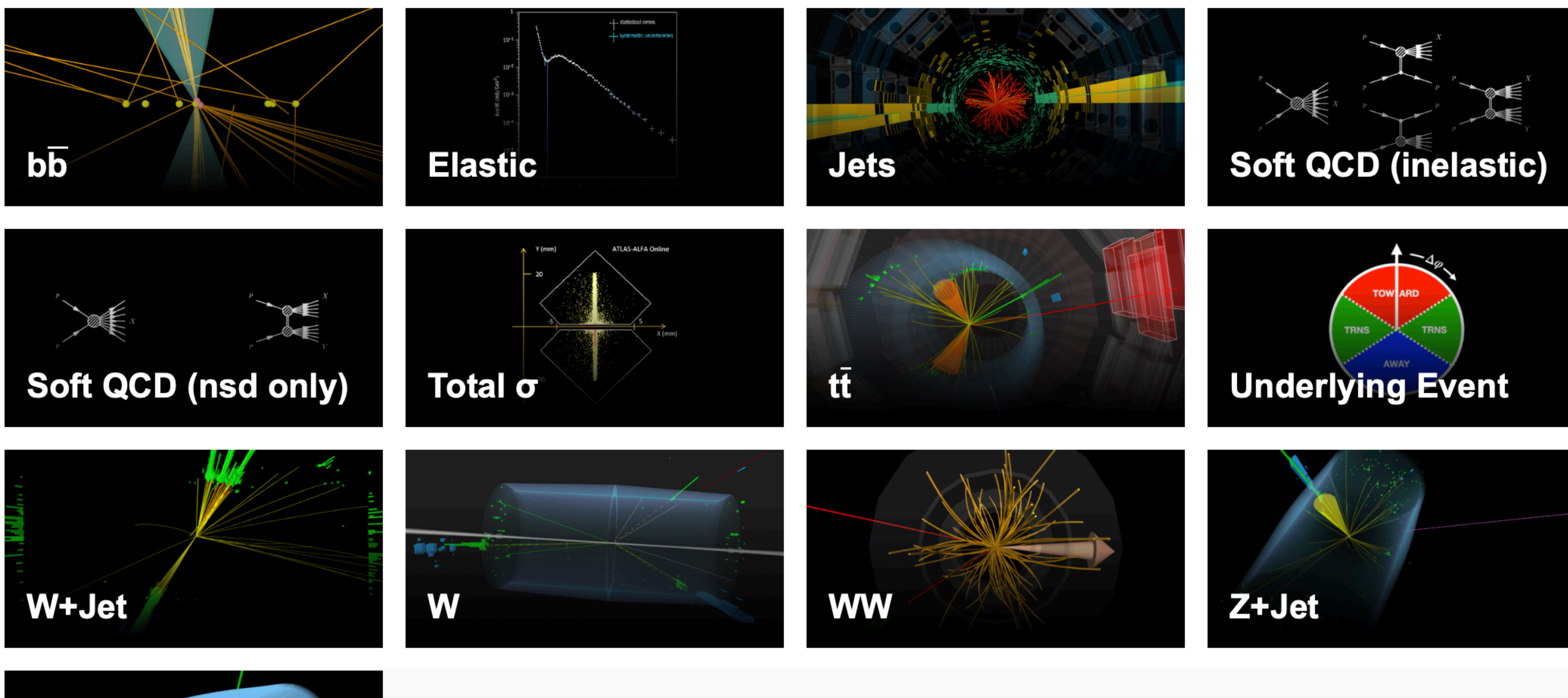
ABOUT | PLOTS ▾ | COMPARISON ▾ | LHC@HOME

Plots by analyses

Preview at mcplots-dev.cern.ch

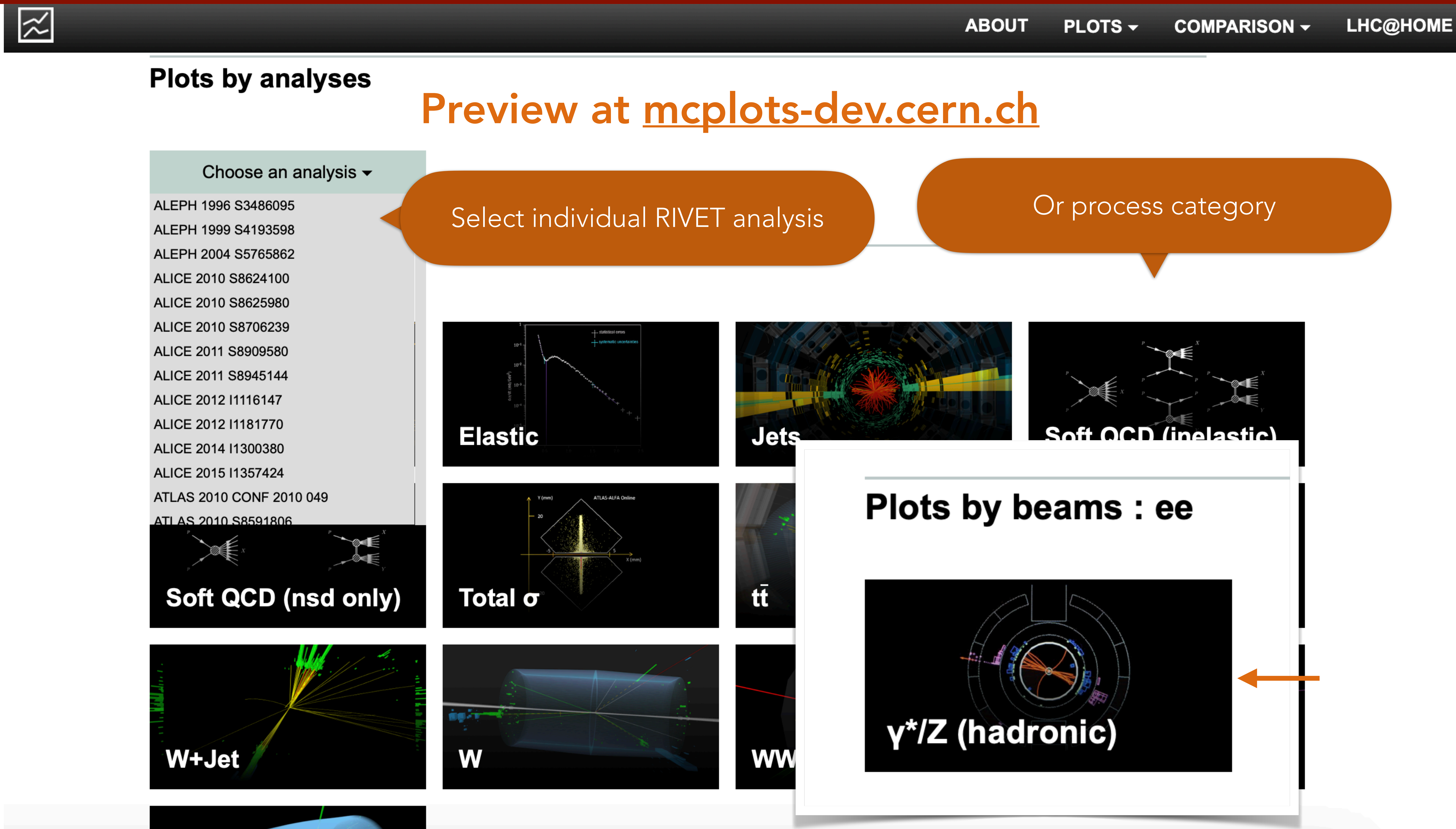
Choose an analysis ▾ ←

Plots by beams : pp



MCPLOTS — New Look Coming Soon

Work in Progress: A. Korneeva, A. Karneyeu, **PS**



MCPLOTS — New Look Coming Soon

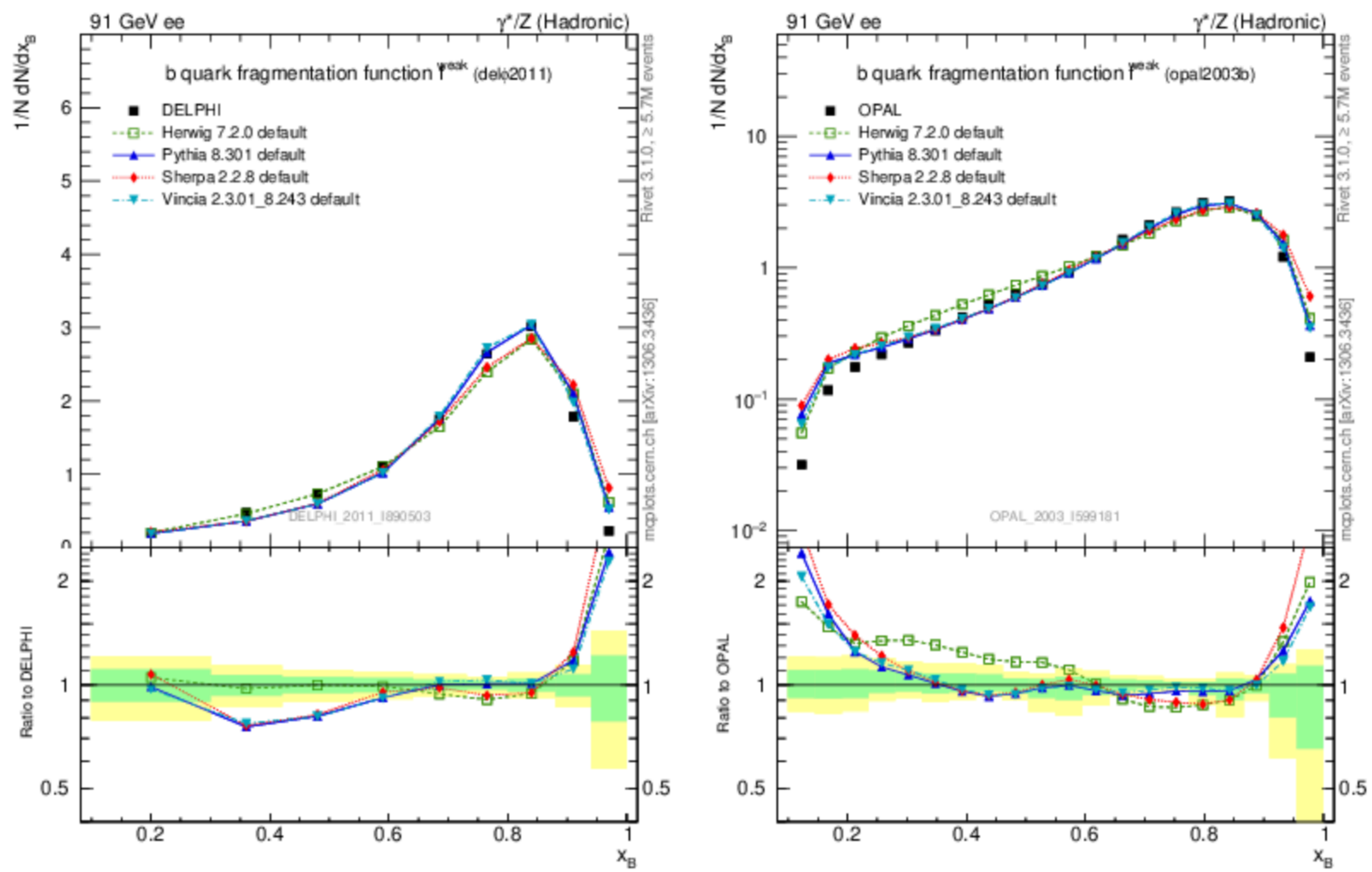
Work in Progress: A. Korneeva, A. Karneyeu, **PS**

ABOUT … HOME

- ΔB(Max-Min)
- C parameter
- D parameter
- EEC
- EEC Asymmetry
- M(Heavy Hemisph)
- M(Light Hemisph)
- ΔM(Heavy-Light)
- Planarity
- Sphericity
- Thrust
- 1-Thrust
- Thrust Major
- Thrust Minor
- Thrust Oblateness
- Charm and Bottom ▴
  - f_{weak}
  - Mean of f_{weak}
  - B multiplicity
  - D multiplicity
  - D^* multiplicity
  - Λ_b multiplicity
  - D^* spectrum

ee @ 91 GeV | General-Purpose MCs : Main ▾ | Customize

Select between all available MC generators & versions

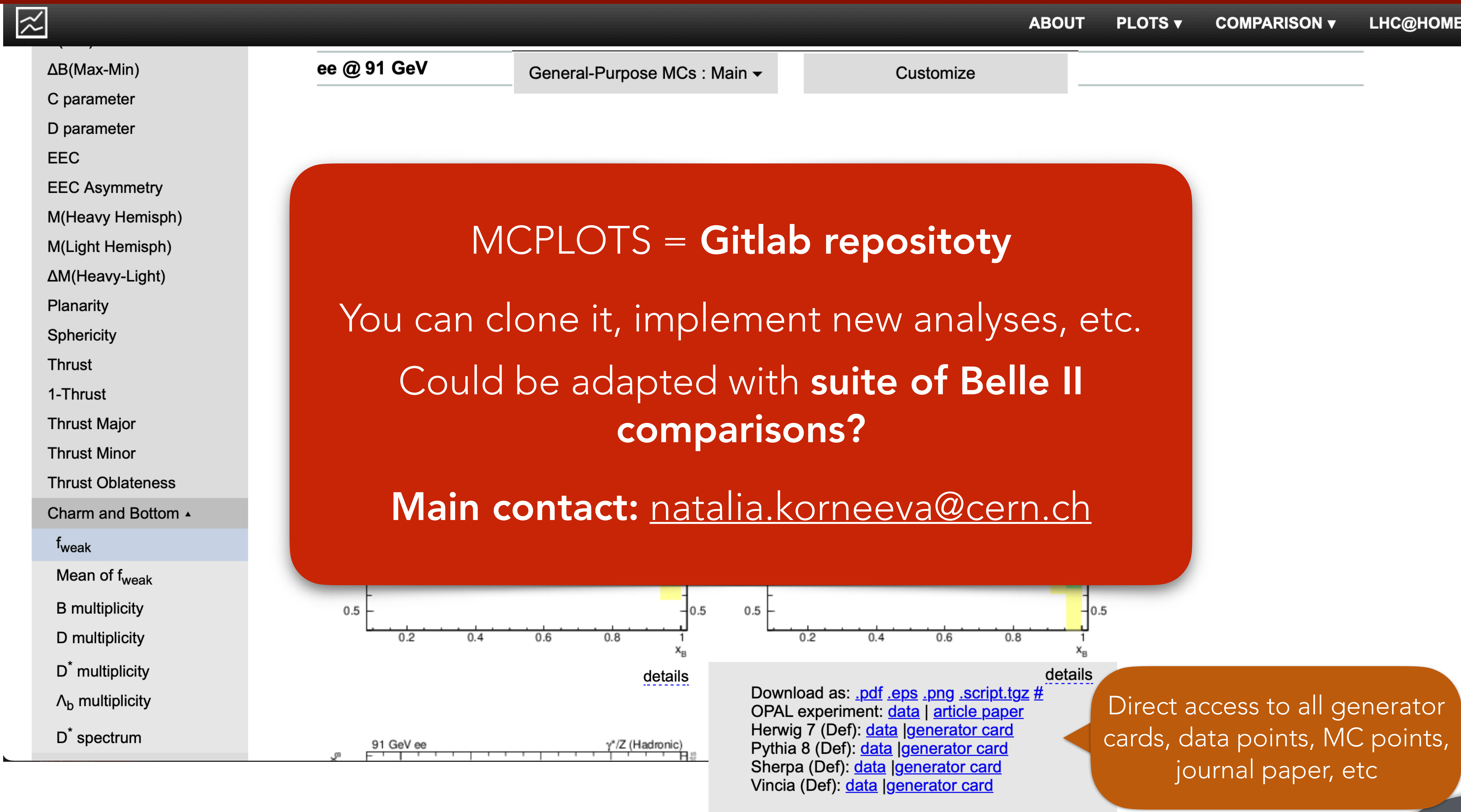


details

details

MCPLOTS — New Look Coming Soon

Work in Progress: A. Korneeva, A. Karneyeu, **PS**



MCPLOTS = **Gitlab repositoty**

You can clone it, implement new analyses, etc.

Could be adapted with **suite of Belle II comparisons?**

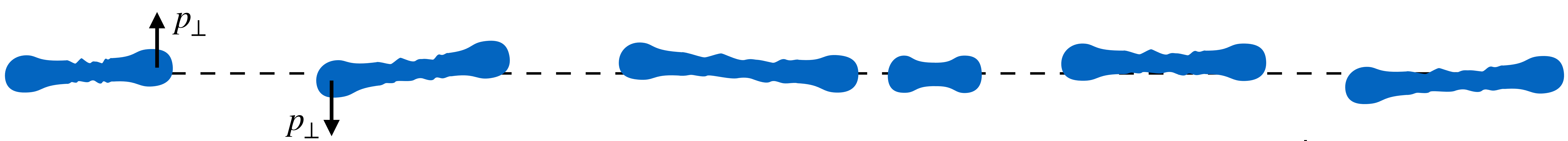
Main contact: natalia.korneeva@cern.ch

Direct access to all generator cards, data points, MC points, journal paper, etc

Extra Slides

[Reweighting MC Predictions & Automated Fragmentation Variations in Pythia 8, 2308.13459]

Transverse Fragmentation Function (Gaussian)

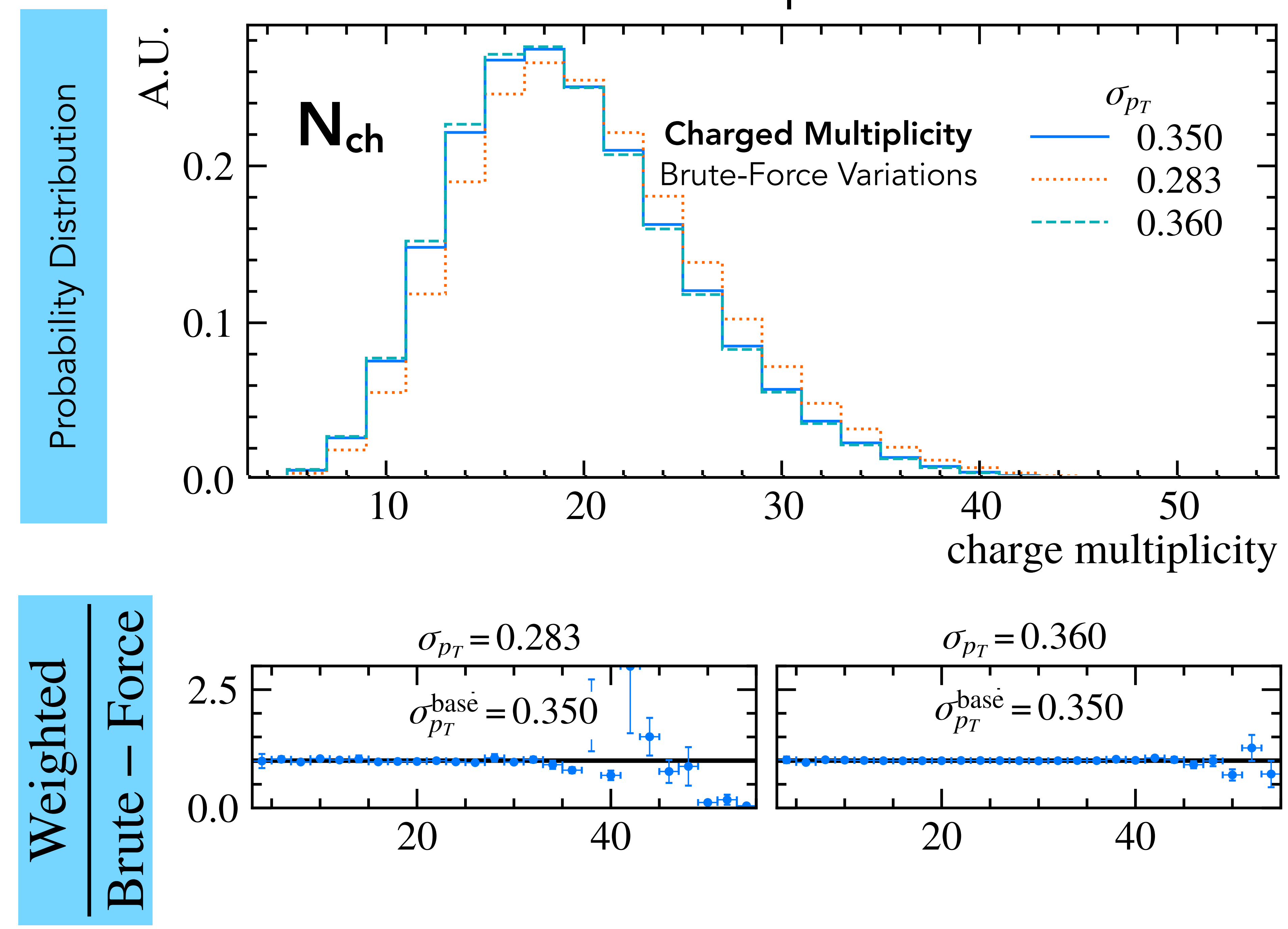


$$\frac{1}{2\pi\sigma_{p_T}^2}\exp\left(-\frac{(\Delta p_x)^2+(\Delta p_y)^2}{2\sigma_{p_T}^2}\right)$$

`StringPT:sigma`

variations →

Example



Reweighting Methodology:

For each p_T (Box-Muller transform):

$$w' = \frac{\sigma^2}{\sigma'^2}\exp\left(-\kappa\left(\frac{\sigma^2}{\sigma'^2}-1\right)\right)$$

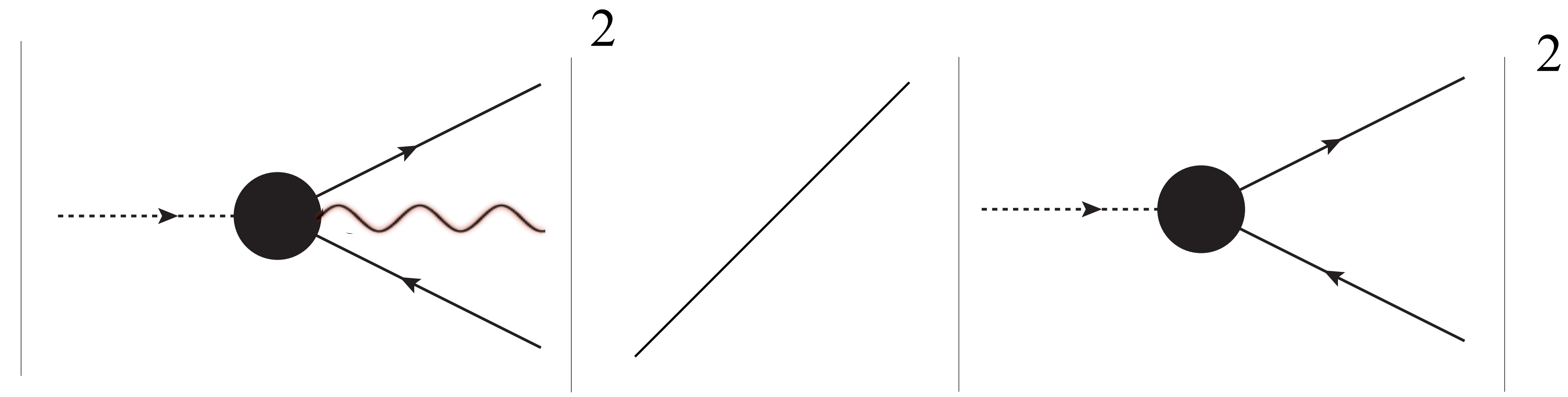
$\kappa = (n_1^2 + n_2^2)/2$ and n_i are normally distributed random variates

1. Types of (QED) Showers

Simple case:

neutral scalar → 2 charged fermions

= **A single QED dipole**



LO QED $\propto \dfrac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}} + \dfrac{1}{M_0^2}\left(\dfrac{s_{\gamma e^+}}{s_{e^-\gamma}} + \dfrac{s_{e^-\gamma}}{s_{\gamma e^+}} + 2\right)$

eikonal term — collinear terms

e^--collinear limit, e^+-collinear limit → PYTHIA **DGLAP**

$$\frac{P_{e^-\to e^-\gamma}(z_1)}{s_{1\gamma}} + \frac{P_{e^+\to e^+\gamma}(z_2)}{s_{2\gamma}}$$

All Singular Terms → VINCIA **Antenna**

$$\frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}} + \frac{1}{M_0^2}\left(\frac{s_{\gamma e^+}}{s_{e^-\gamma}} + \frac{s_{e^-\gamma}}{s_{\gamma e^+}}\right)$$

Soft limit → HERWIG, SHERPA, PHOTOS **YFS**

$$\frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}}$$

Note: this is (intentionally) oversimplified. Many subtleties (recoil strategies, gluon parents, initial-state partons, and mass terms) not shown.

Beyond 2-body Systems: QED Multipoles

PYTHIA QED

Determines a "best" set of dipoles. No genuine multipole effects.

I.e., interference beyond dipole level only treated via "principle of maximal screening"

Works as a parton shower evolution (+ MECs) ➤ interleaved with QCD, MPI, …

YFS QED [Yennie-Frautschi-Suura, 1961 ➤ several modern implementations]

Allows to take full (multipole) soft interference effects into account

"Scalar QED"; no spin dependence.

I.e., starts from purely soft approximation; collinear terms not automatic

Is not a shower; works as pure afterburner, adding a number of photons to a final state with predetermined kinematics; no interleaving

VINCIA QED [Kleiss-Verheyen, 2017 ➤ Brooks-Verheyen-PS, 2020]

Allows to take full (multipole) soft interference effects into account

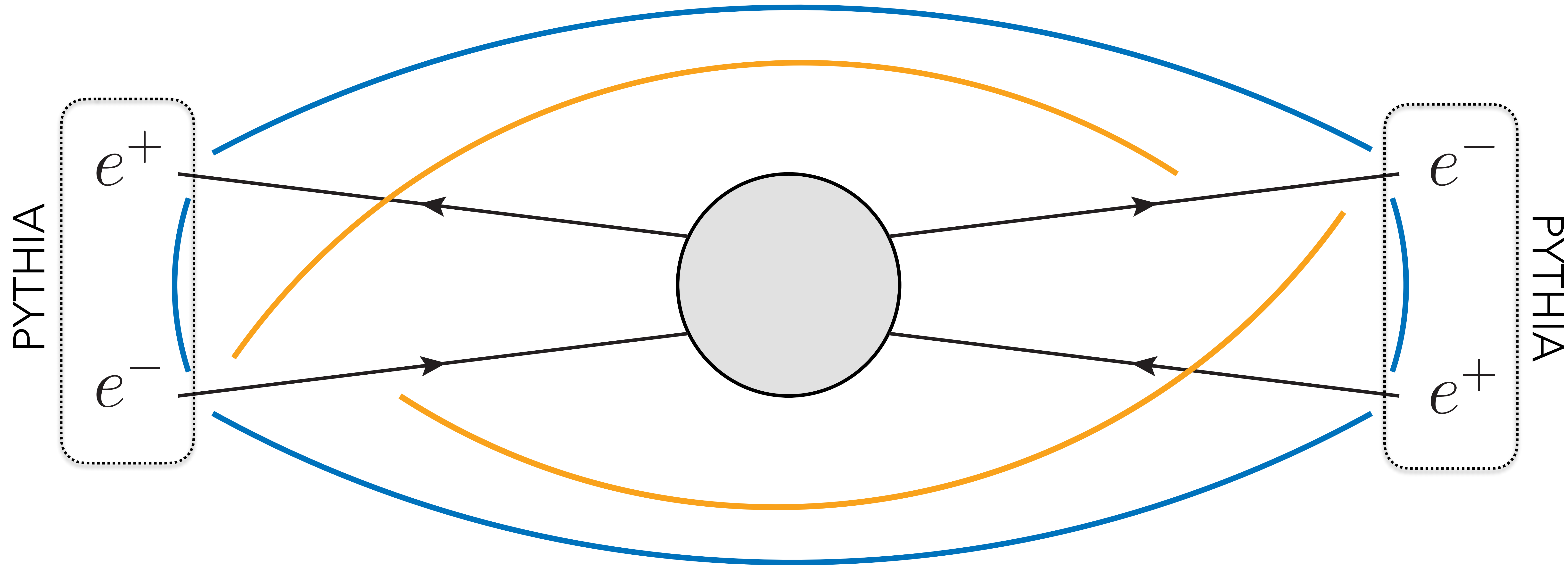
Not limited to scalar QED; includes spin dependence

I.e., starts from antenna approximation; including collinear terms

Works as a parton shower evolution; can be interleaved (+ MECs).

What´s the problem?

Example: Quadrupole final state (4-fermion: $e^+e^+e^-e^-$)



Why was this not done as a shower before?

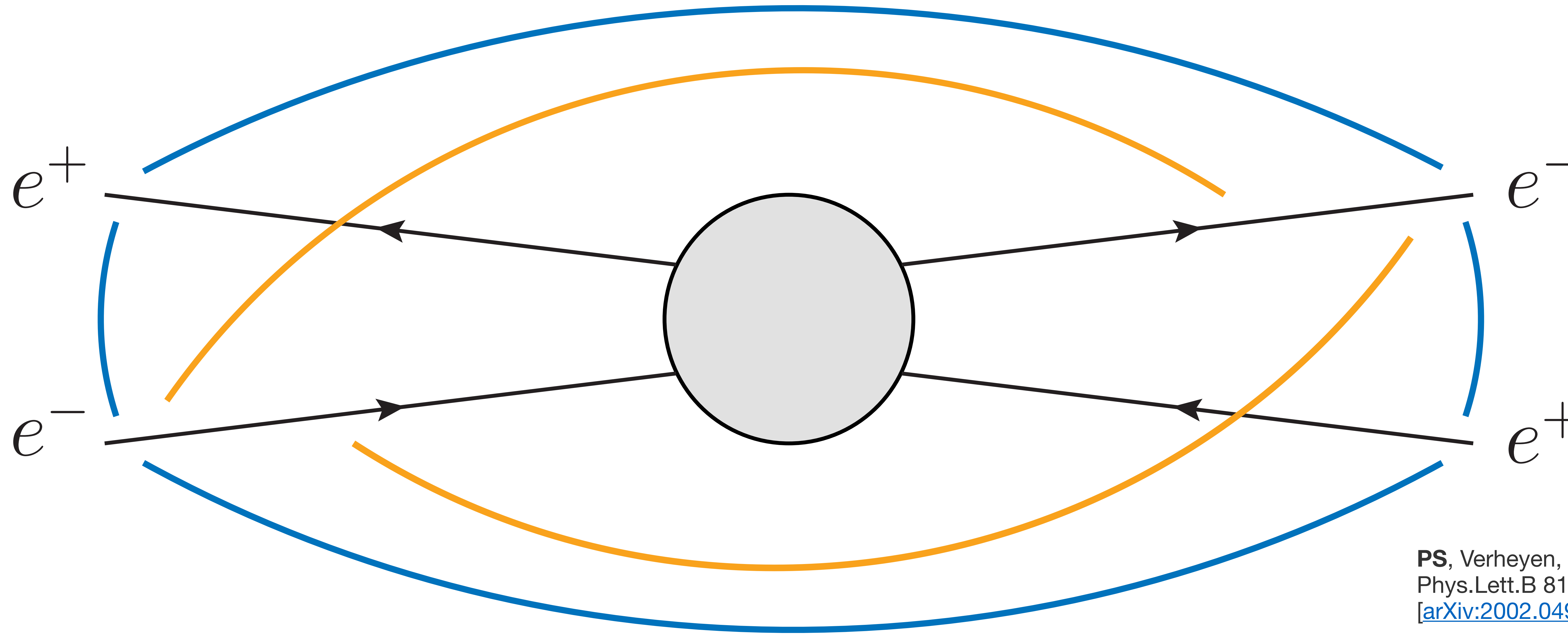
The orange terms are negative ➤ negative weights (+ big cancellations)

YFS gets around that by not being formulated as a shower (& no spin dependence)

Utilises that the sum is always non-negative.

What does VINCIA do differently?

Example: Quadrupole final state (4-fermion: $e^+e^+e^-e^-$)



PS, Verheyen, Phys.Lett.B 811 (2020) 135878 [arXiv:2002.04939]

Sectorize phase space: for each possible photon emission kinematics p_γ, find the 2 charged particles with respect to which that photon is softest ➤ "Dipole Sector"

Use dipole *kinematics* for that sector, but sum **all** the positive and negative *antenna* terms (w spin dependence) to find the **coherent emission *probability***.

Further Details

Antenna phase-space factorisation is exact, also for massive particles

+ Universal mass corrections are included in the eikonals

➤ Should have extremely faithful representation of "dead cone" effect (radiation from massive particles strongly damped for $\theta_\gamma \lesssim E/m$) [Gehrmann-de Ridder, Ritzmann, PS, 2012]

Also automatically includes $\gamma \to e^+e^-, \mu^+\mu^-, \ldots$ splittings (not in PHOTOS? YFS?)

➤ **First steps towards application of VINCIA QED to Hadron Decays**

Honours project of Giacomo Morgante (Monash, 2023, in collaboration with Warwick)

+ Can incorporate Matrix-Element Corrections [Giele, Kosower, PS, 2011, + more recent]

Not implemented yet. Techniques known; worked out focusing on QCD

Will affect tails of hard radiation (process-dependent non-singular terms), so this is potentially an important still missing feature. Also: Form Factors, VMD contributions, BRs, …

+ Can be interleaved with event evolution, e.g., with Resonance Decays