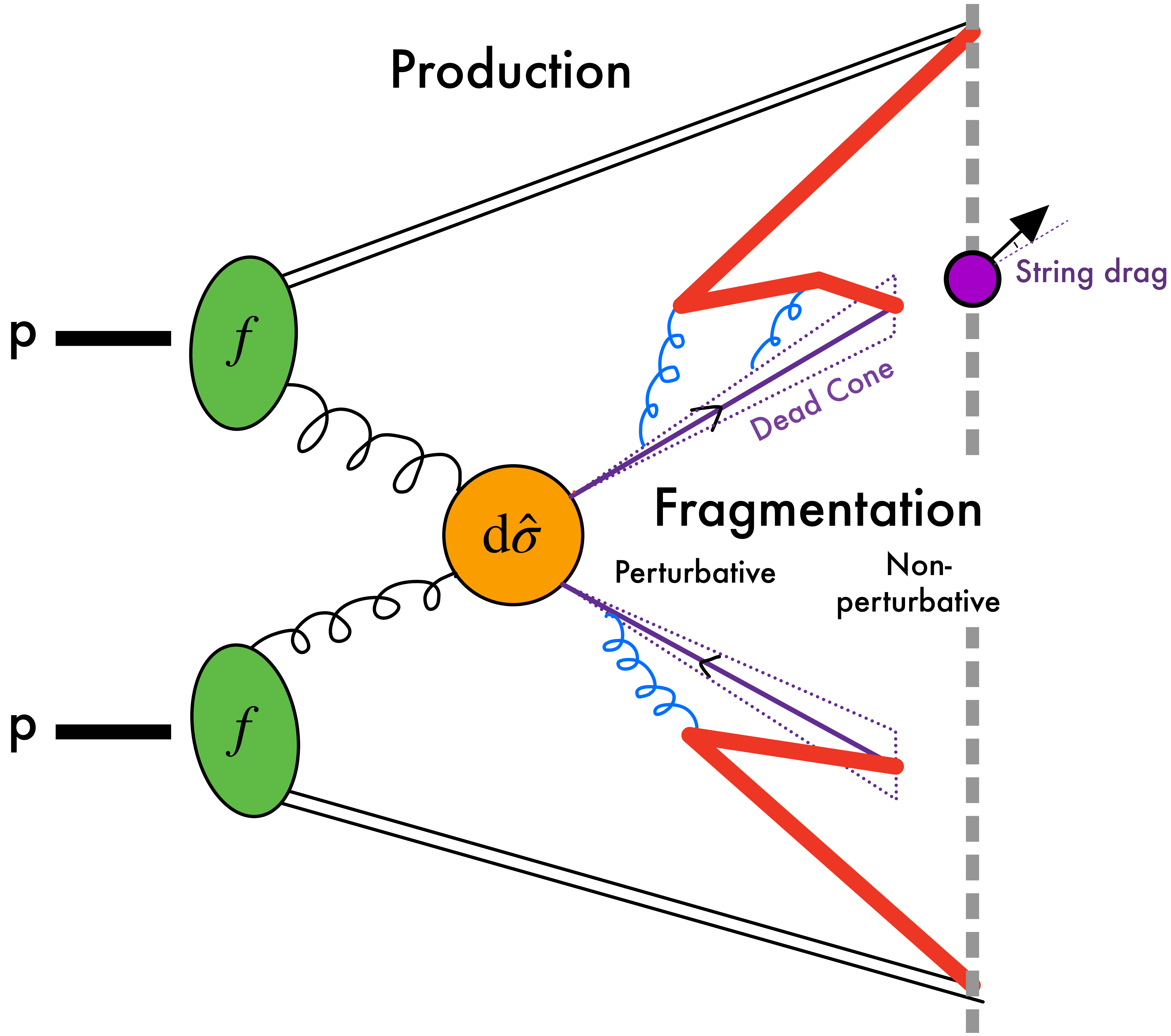
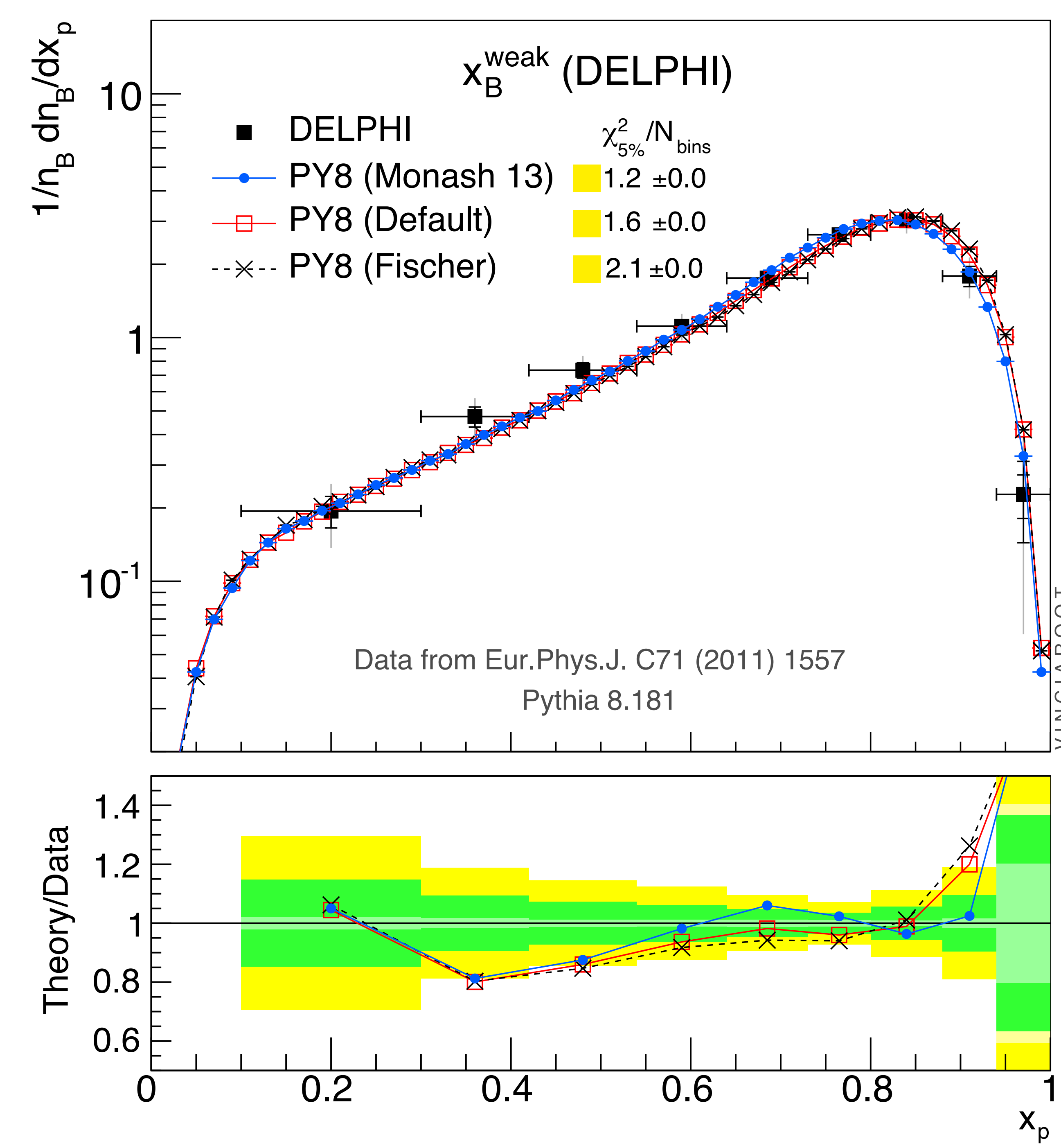
Heavy Flavours in PYTHIA — Status and News

Peter Z Skands — U of Oxford & Monash U



Tuning



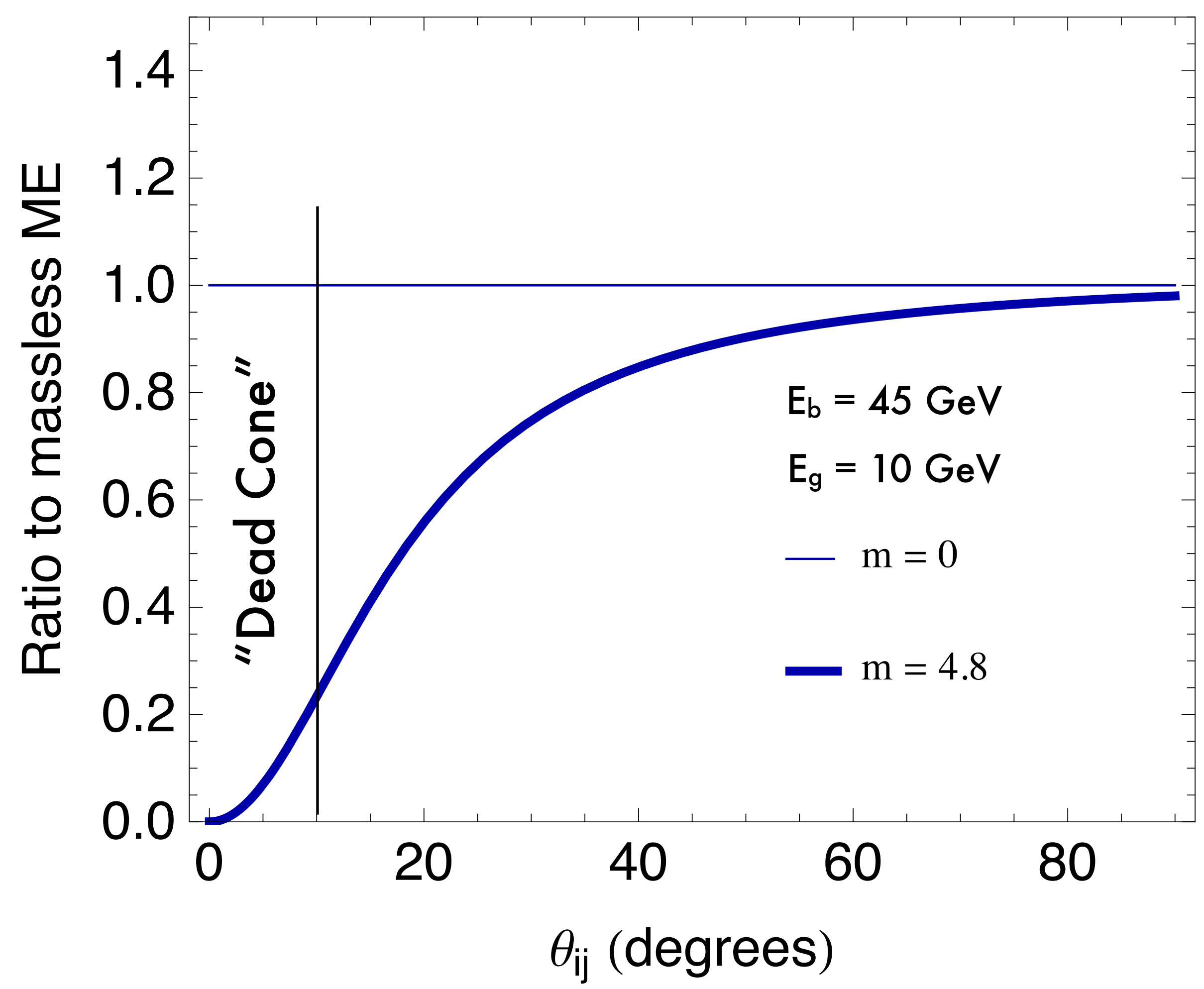
⊗ Decay(s) ⊗ QED Radiation

Gehrmann-de Ridder, Ritzmann, PZS, 1108.6172

Exact Phase Space

Dalitz Plots: ⟶

Eikonal Mass Corrections



(a) $Q\bar{q} \to Qg\bar{q}$ (Q massive, $\bar{q}$ massless)

(b) $q\bar{q} \to qg\bar{q}$ (q massless)

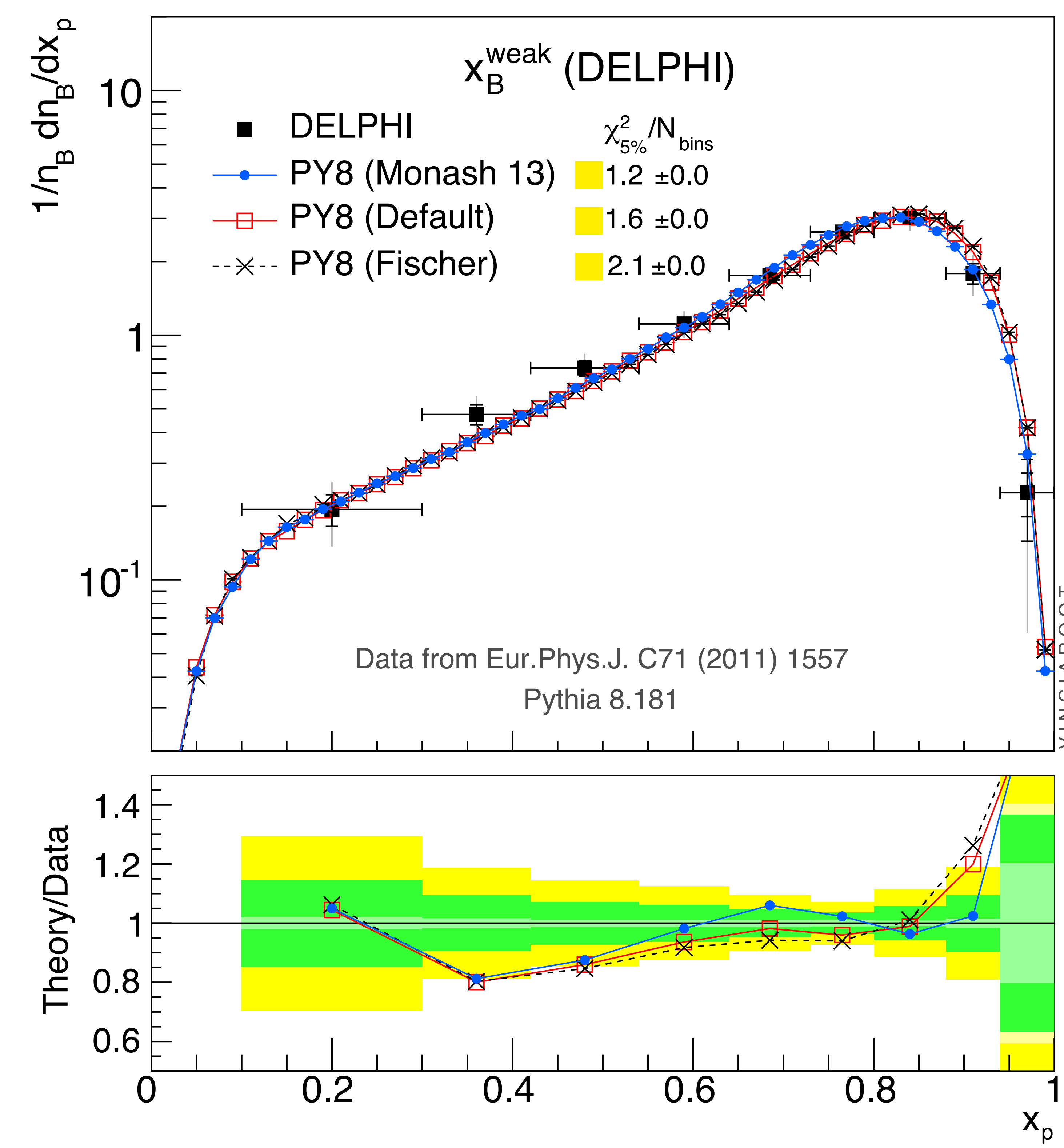
(+ analogous ones for $g \to Q\bar{Q}$)

Combination of phase space and mass corrections $\Longrightarrow$ Dead Cone for $\theta \lesssim \dfrac{m}{E}$

Also: careful treatment of "quasi-collinear" limit + Soon: iterated MECs.

B spectrum = Perturbative Fragmentation (α_s) ⊗ Lund-Bowler Fragmentation Function:

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



Monash Tune

Light-flavour event shapes → α_s

N_{ch} and x_{ch} spectra → Lund a and b parameters

ALEPH D* spectrum → r_c

DELPHI & SLD B spectra → r_b

Interplay between matching, retuning, and HF fragmentation (r_c, r_b, etc) needs dedicated study?

Aware of some efforts. Coordinated? Person-power … ?

Alternatives?

By default, Peterson (or similar) not consistent with string fragmentation, but …

Note on Heavy-Flavour Tagging

Taggers trained on combination of data-driven & MCs

Performance (& Uncertainties!) depend (at least partially?) on:

Fidelity of MC modelling

+ in-situ constraints

Fundamental physics of confinement not a solved issue

LHC discoveries: Strangeness and baryon enhancements, collectivity, …

➜ New (more advanced) MC hadronizaton models are being developed

Colour reconnections,

Octet (gluon) vs triplet (quark) fragmentation,

Colour ropes,

String Junctions

Coalescence

Close-packing,

String interactions,

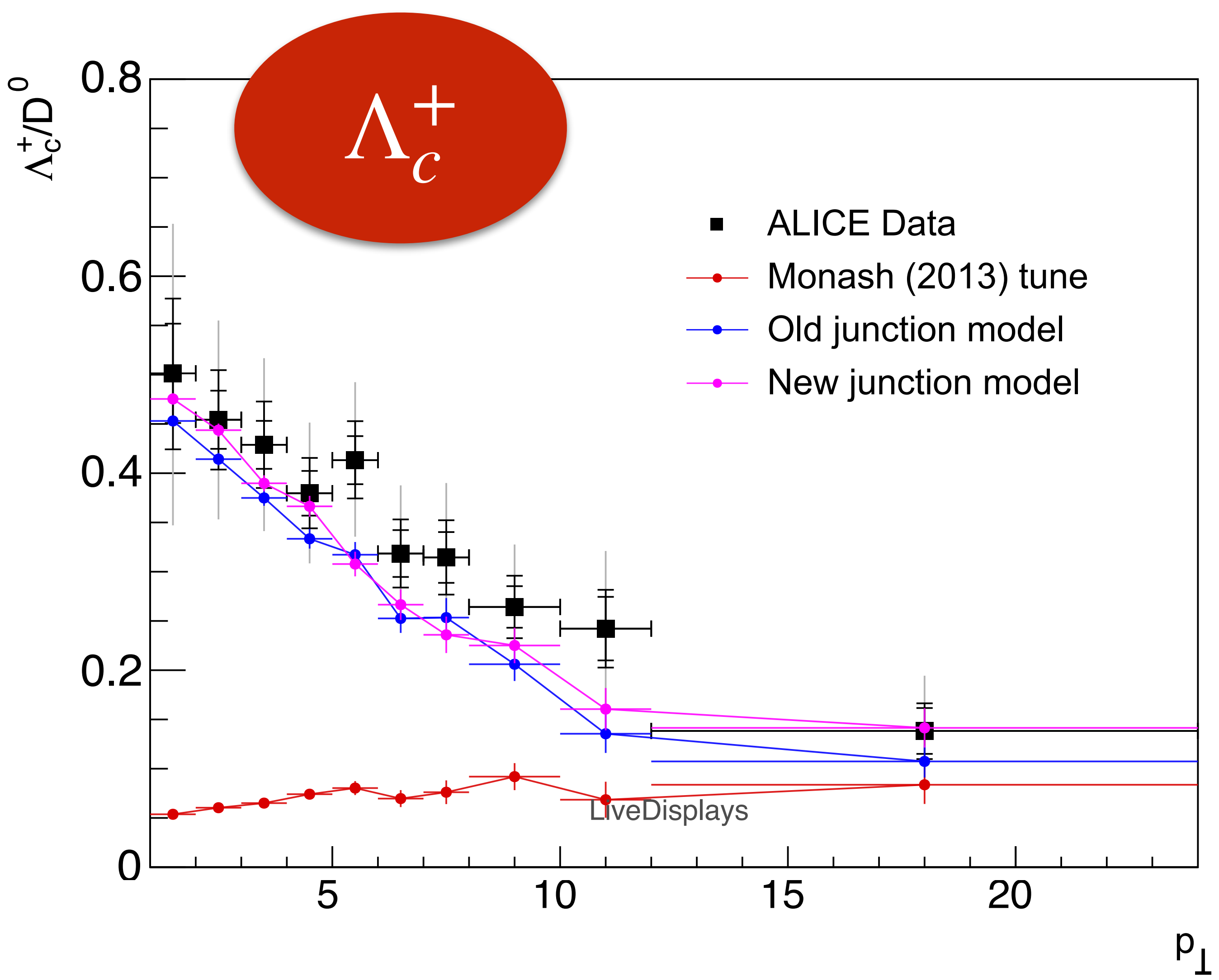
Flow / String Shoving,

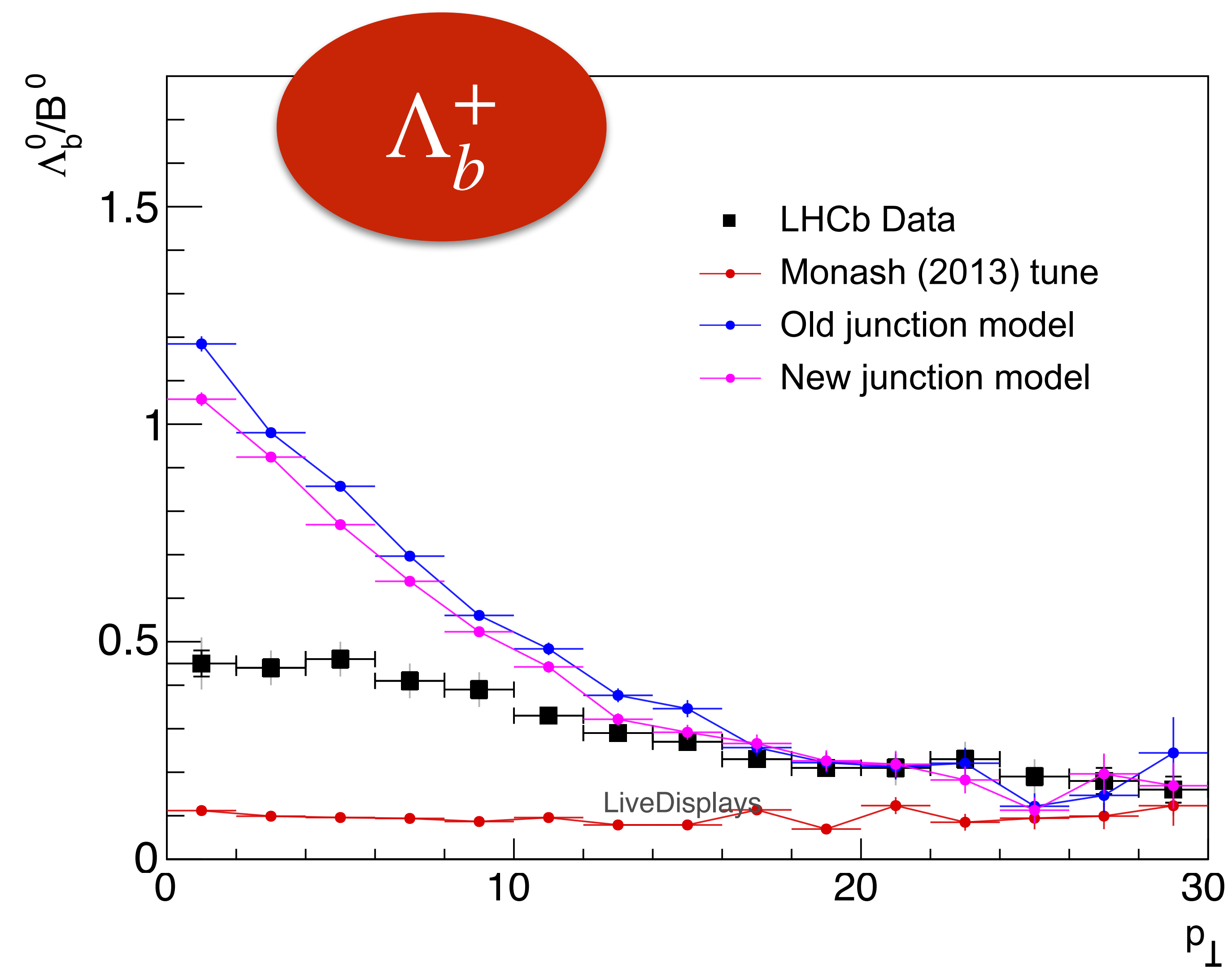
Hot strings,

Excited strings,

…

Recent Example: Heavy-Flavour Baryons at Low p_T

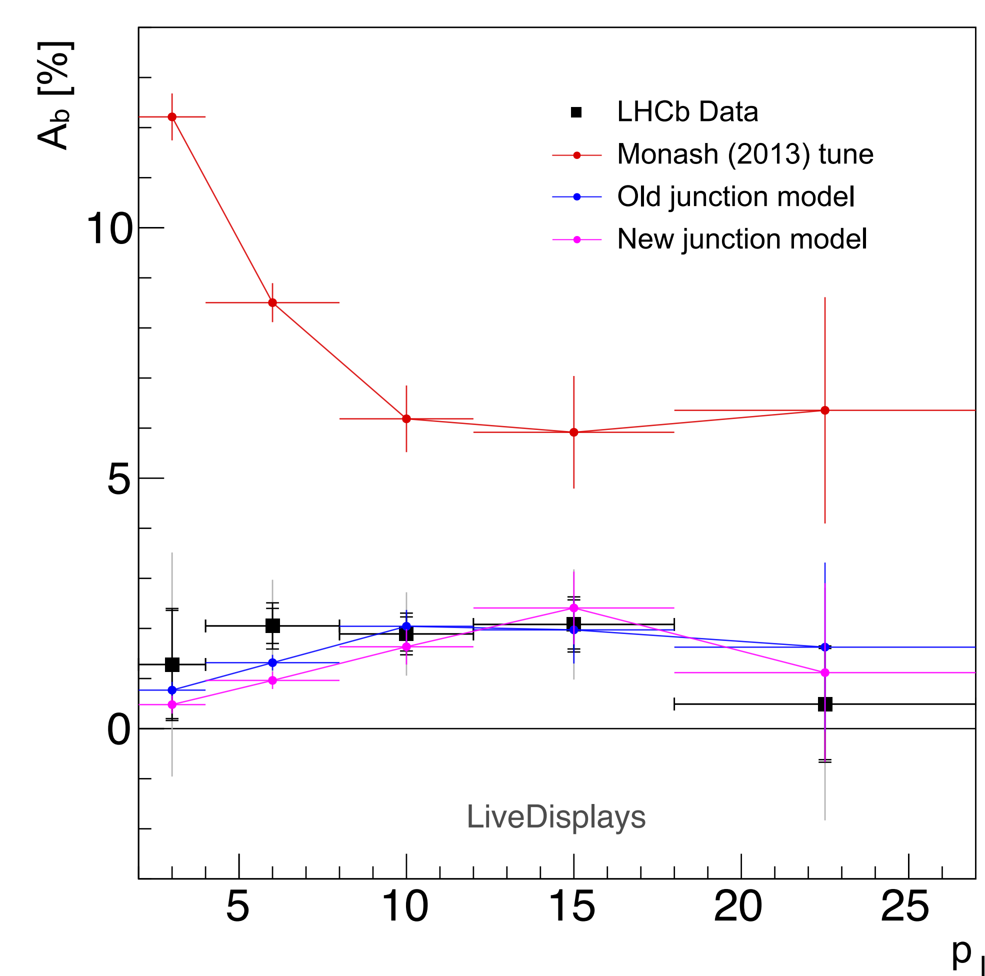


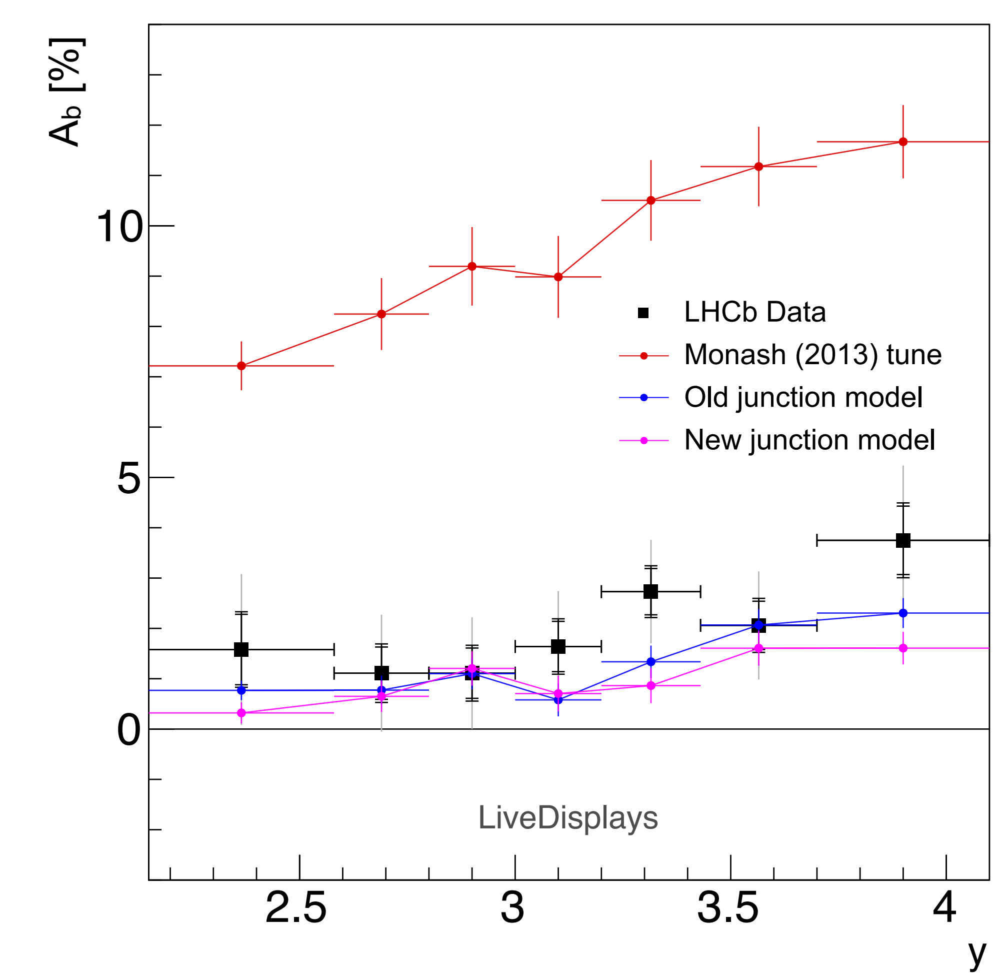


String Formation Beyond Leading Colour,
Christiansen & PZS, 1505.01681

New: *String Junctions Revisited,*
Altmann & PZS, 2404.12040

Also: baryon asymmetry diluted by extra baryon pairs





(+ Onium Production)

Hard Processes

NRQCD MEs

Question: not totally clear how to match the two

New: "Fragmentation"

Shower with $g \to \mathrm{Onium} + X$

(LETO — P. Ilten & N. Cooke 2312.05203)

+ Colour Reconnections?

"Accidental" low-mass $Q\bar{Q}$ singlets

(depends on CR assumptions & rate of low-mass $Q\bar{Q}$ pairs)

Related: PYTHIA study of Bc and other doubly-heavy hadrons via MPI + CR, T. Hadavizadeh et al., 2205.15681

Question: space-time suppression due to small size?

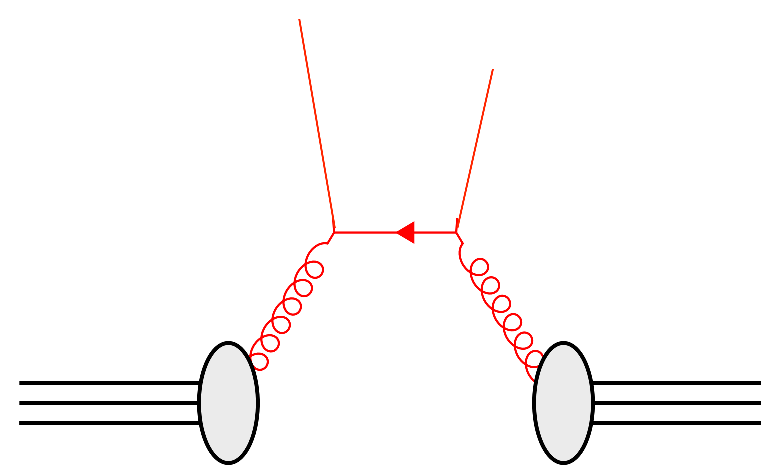
Optimisation

Egede, Hadavizadeh, Singla, PZS, Vesterinen, 2205.15681:

Userhooks

Inspect the event and ***veto*** if there isn't what we want

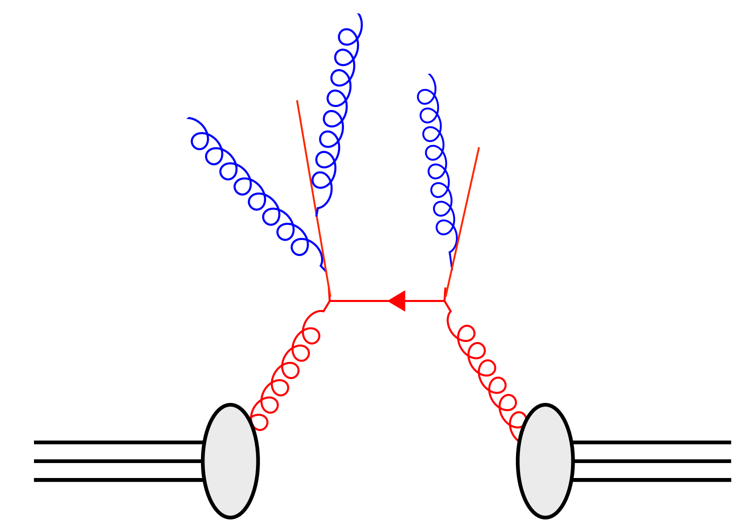
We can check at difference energy scales μ



$\mu = \sqrt{s}$

Is there the required heavy quark, or enough energy to create one?

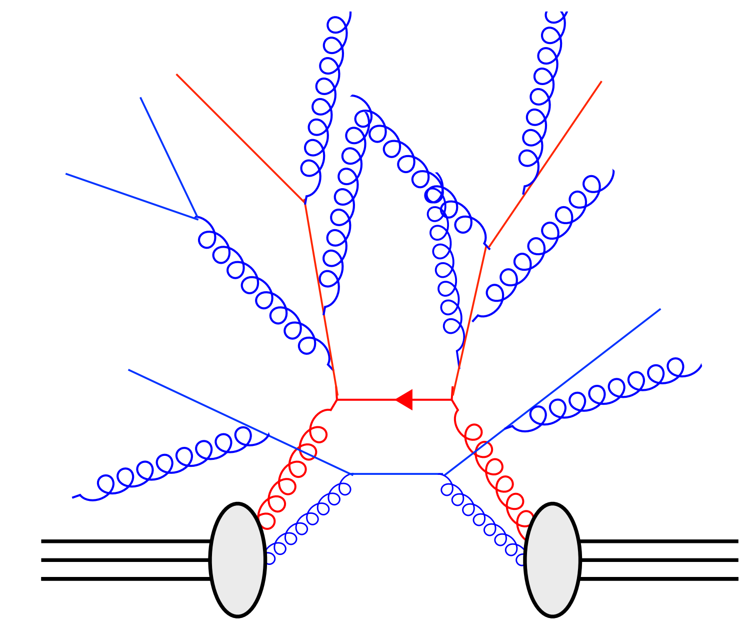
Yes →
No ↓ **Try again**



$\mu = m_b$

Is there the required heavy quark?

Yes →
No ↓ **Try again**



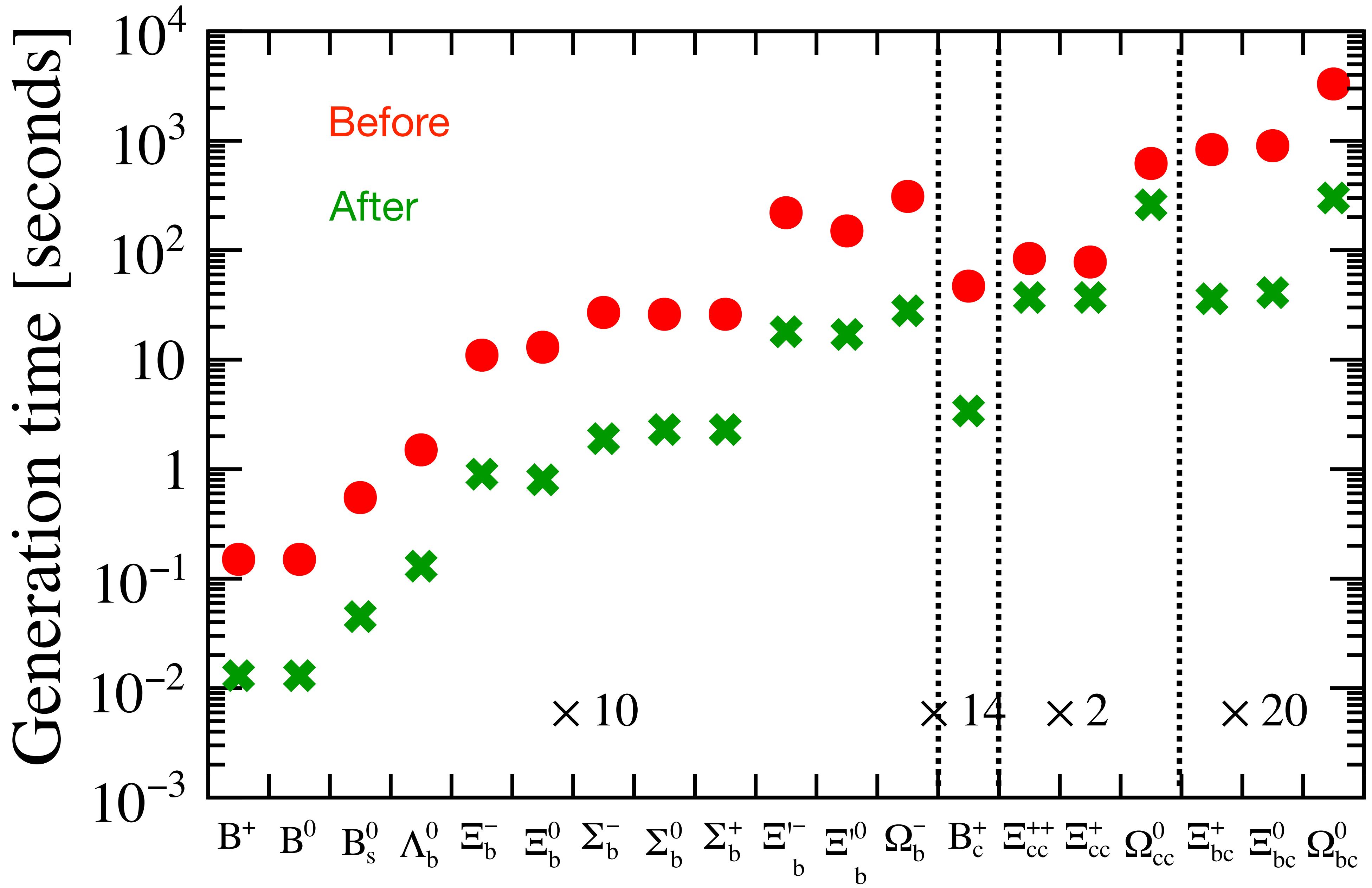
$\mu = \Lambda_{QCD}$

Are there the required heavy quarks? (If you want more than one)

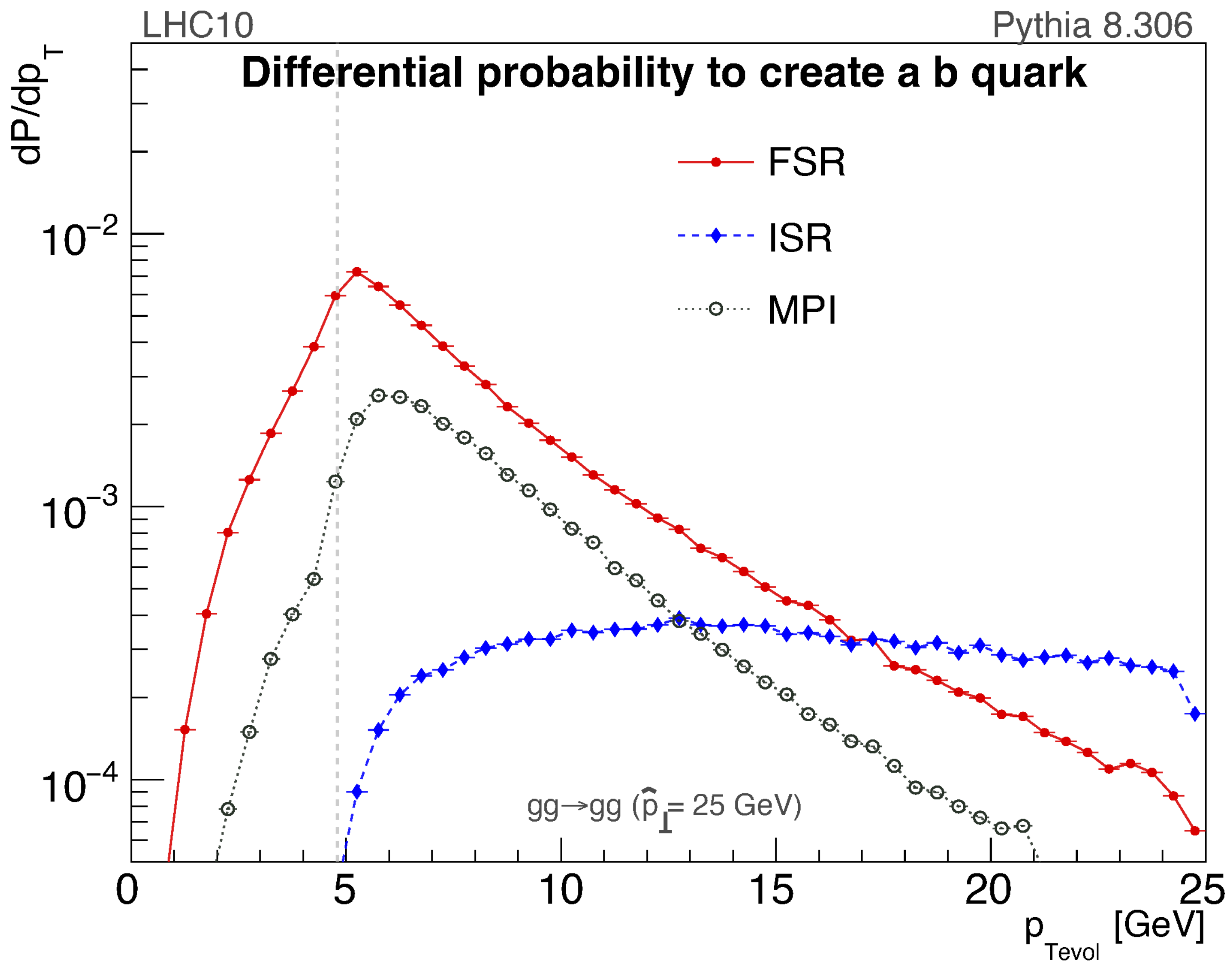
Yes → **Keep!**
No ↓ **Try again**

Saves time spent evolving and hadronising events that would be discarded

Speed Gains & Subtlety



These user hooks have **significantly** reduced generation times



Current implementation isn't perfect

- Small probability for heavy quarks to be produced at scales *below* their mass

➜ Work in progress with T. Hadavizadeh

PYTHIA & B Decays — Recent collaboration with EVTGEN (Warwick)

MONASH WARWICK ALLIANCE

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

Passed back to PYTHIA for re-hadronisation (with simple phase-space models).

How reliable is this modelling? Not aware anyone has looked closely 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 … ?

Example: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.101.092004

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

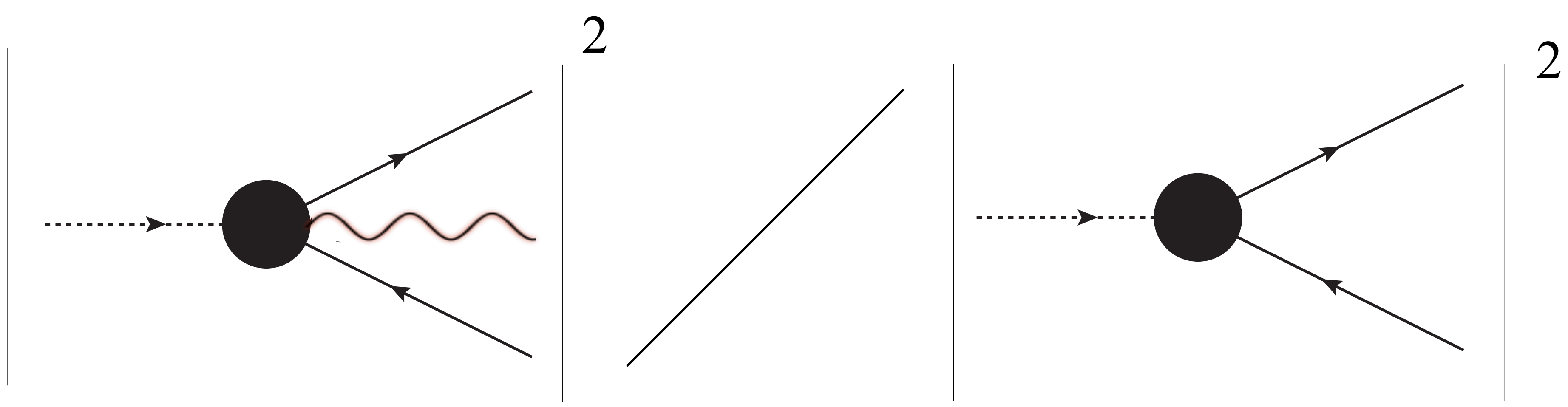
$\Longrightarrow$ matching, merging, finite-width effects, form factors?, …

Types of (QED) Showers

Simple case:

neutral scalar → 2 charged fermions

= **A single QED dipole**



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

eikonal term — collinear terms

PYTHIA

DGLAP

e^--collinear limit — e^+-collinear limit

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

VINCIA

Antenna

All Singular Terms

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

Soft limit

HERWIG, SHERPA, PHOTOS

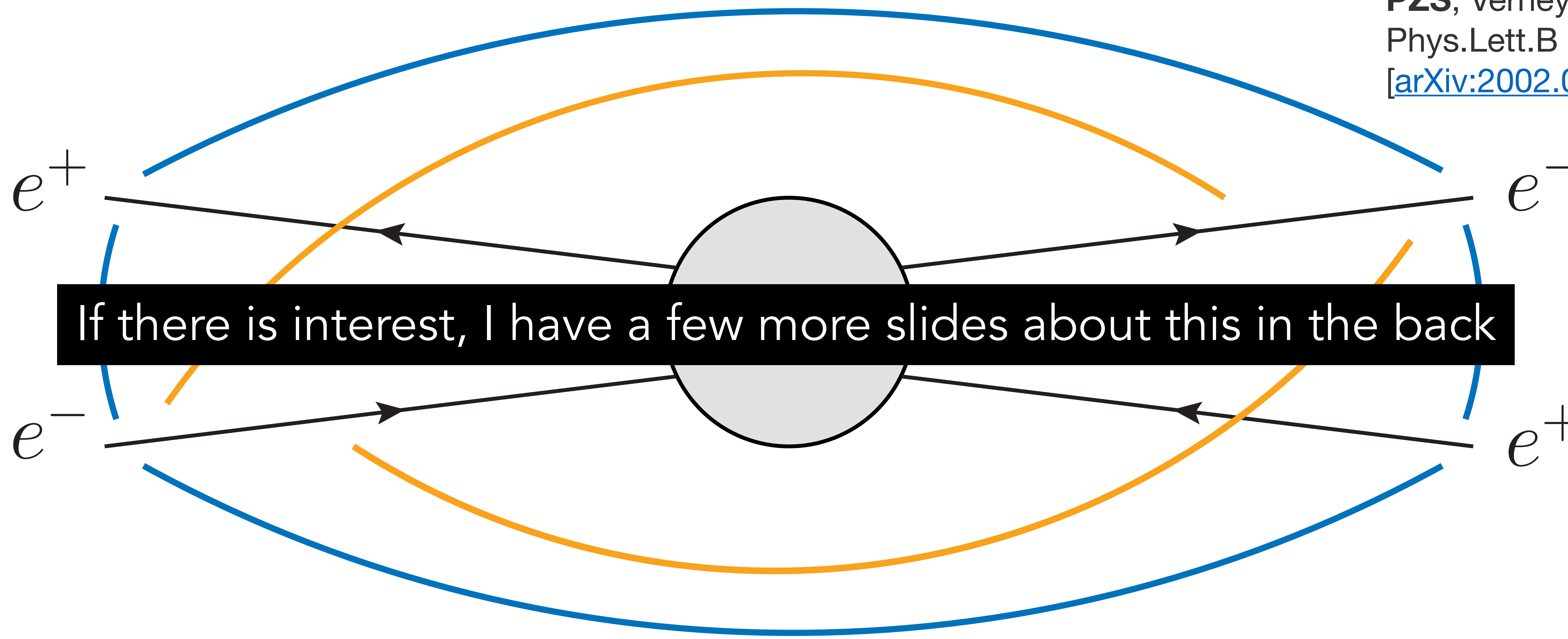
YFS

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

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

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

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



If there is interest, I have a few more slides about this in the back

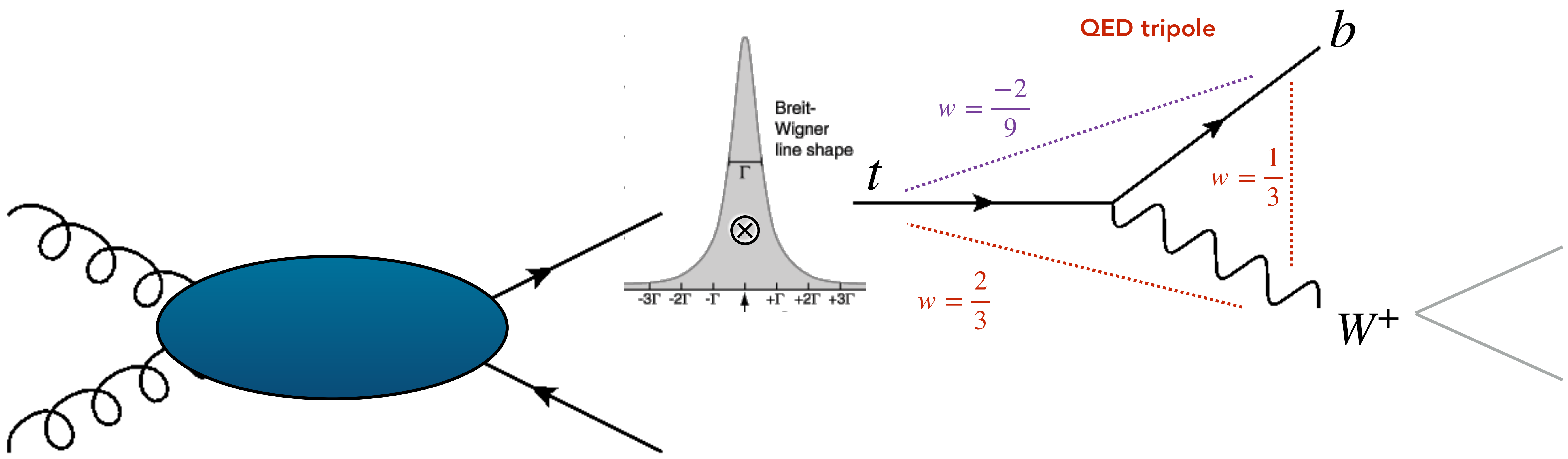
Soft Photon Emission:
[Dittmaier, 2000]

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

- Opposite-charge pairs ➤ positive terms (blue lines)
- Same-charge pairs ➤ negative terms (orange lines)

Conventional "sequential" treatment

Treat each decay (sequentially) as if alone in the universe



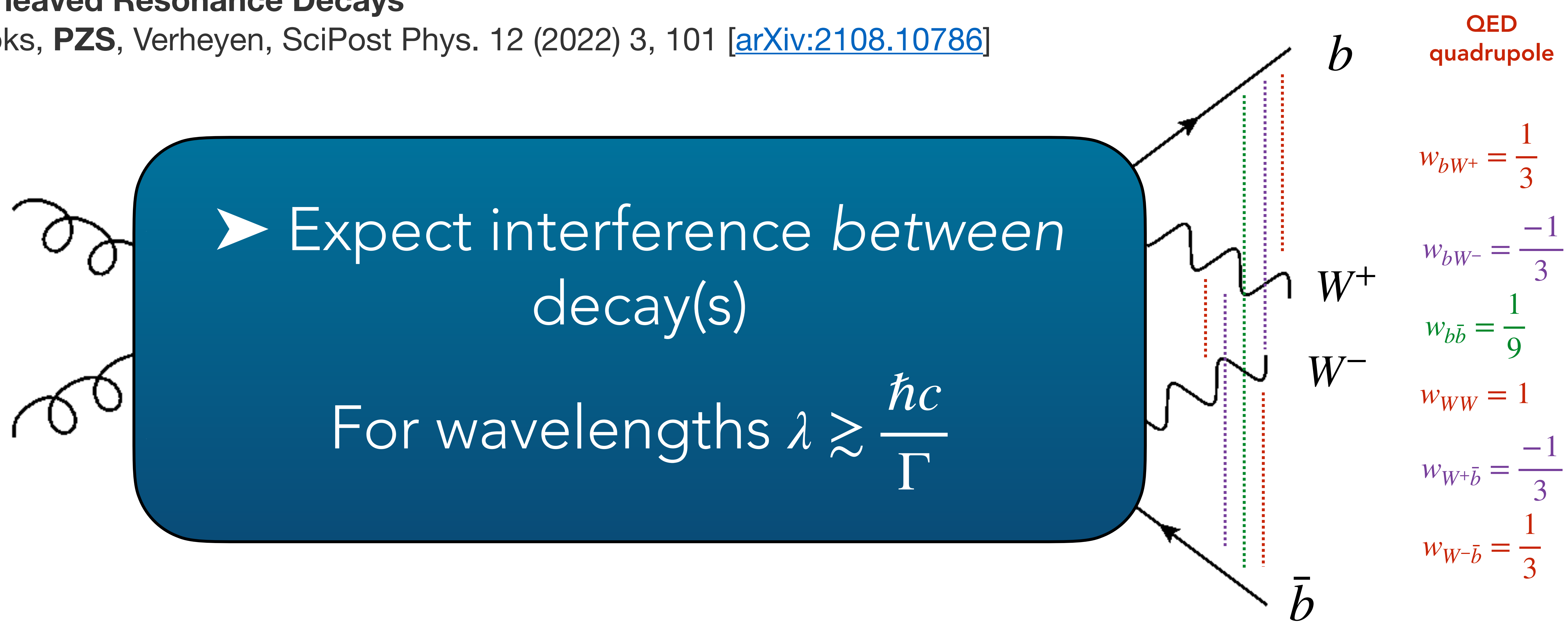
Question:

What about radiation at energies $E_\gamma \lesssim \Gamma_t$ (and $E_\gamma \lesssim \Gamma_W$)?

What does a long-wavelength photon see?

It should not be able to resolve the (short-lived) intermediate state

Interleaved Resonance Decays
Brooks, **PZS**, Verheyen, SciPost Phys. 12 (2022) 3, 101 [arXiv:2108.10786]



Should affect radiation spectrum, for energies $E_\gamma \lesssim \Gamma$

+ Interferences and recoils *between* systems => ***non-local BW modifications***

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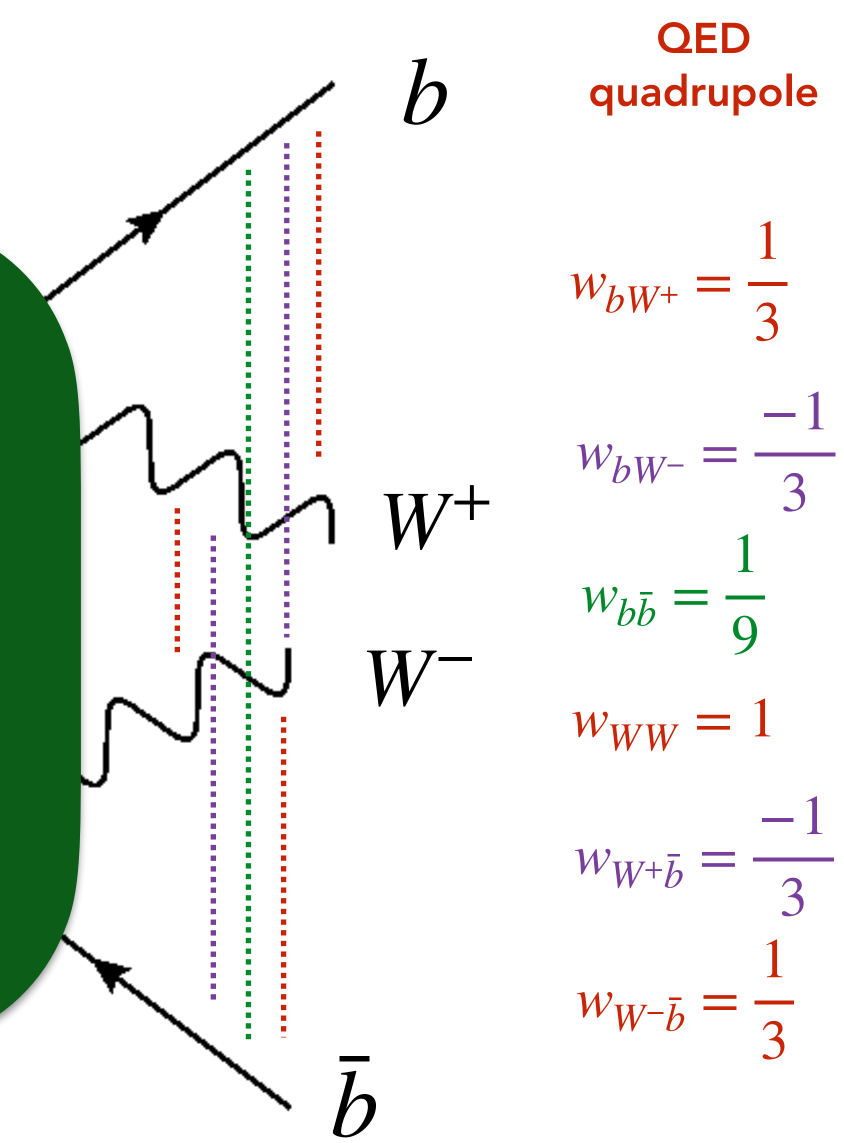
Idea: apply this to Hadron Decays + QED

=> Sophisticated Model of interplay between radiation and decays (finite-width effects, beyond NWA)



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Summary / Plans

During 2024: New Pythia Tuning, to replace Monash Tune as default

What input/constraints/requirements are crucial for you?

Continue work on heavy-flavour baryons & HF+strangeness

String Junctions Revisited arXiv:2404.12040

[…] heavy quarks hadronization: from leptonic to heavy-ion collisions 2405.19137

Optimisation

Improved mass thresholds in PYTHIA's FSR & MPI algorithms, with T. Hadavizadeh (Monash).

Forced hadronization to specific species, with weights calculated, instead of re-hadronization.

Decays

New Project with Warwick/EvtGen to apply new state-of-the-art perturbative techniques to hadron decays, including:

QED Multipole Showers, Modern Fixed-Order Matching Techniques (e.g., MECs), **Interleaved Resonance Decays**

New theory post doc starting at Monash in October: Jack Helliwell (+ F. Abudinen at Warwick.)

Iterated MECs in VINCIA

Extra Slides

Simple case:

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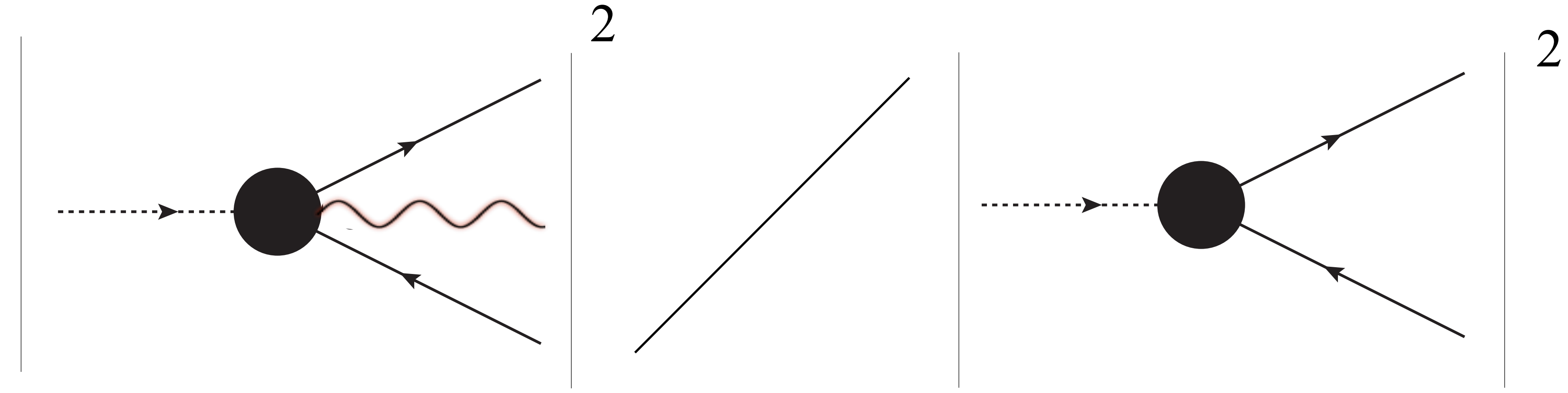
= **A single QED dipole**



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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

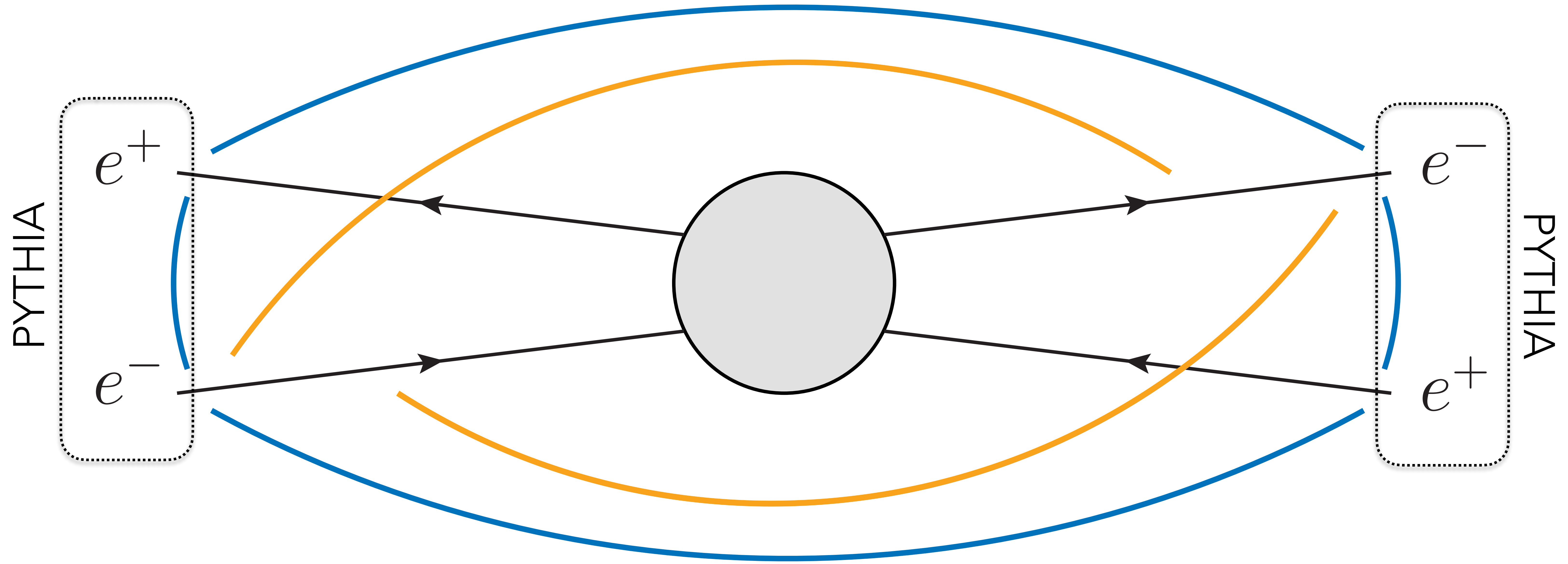
Not limited to scalar QED; includes spin dependence

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?

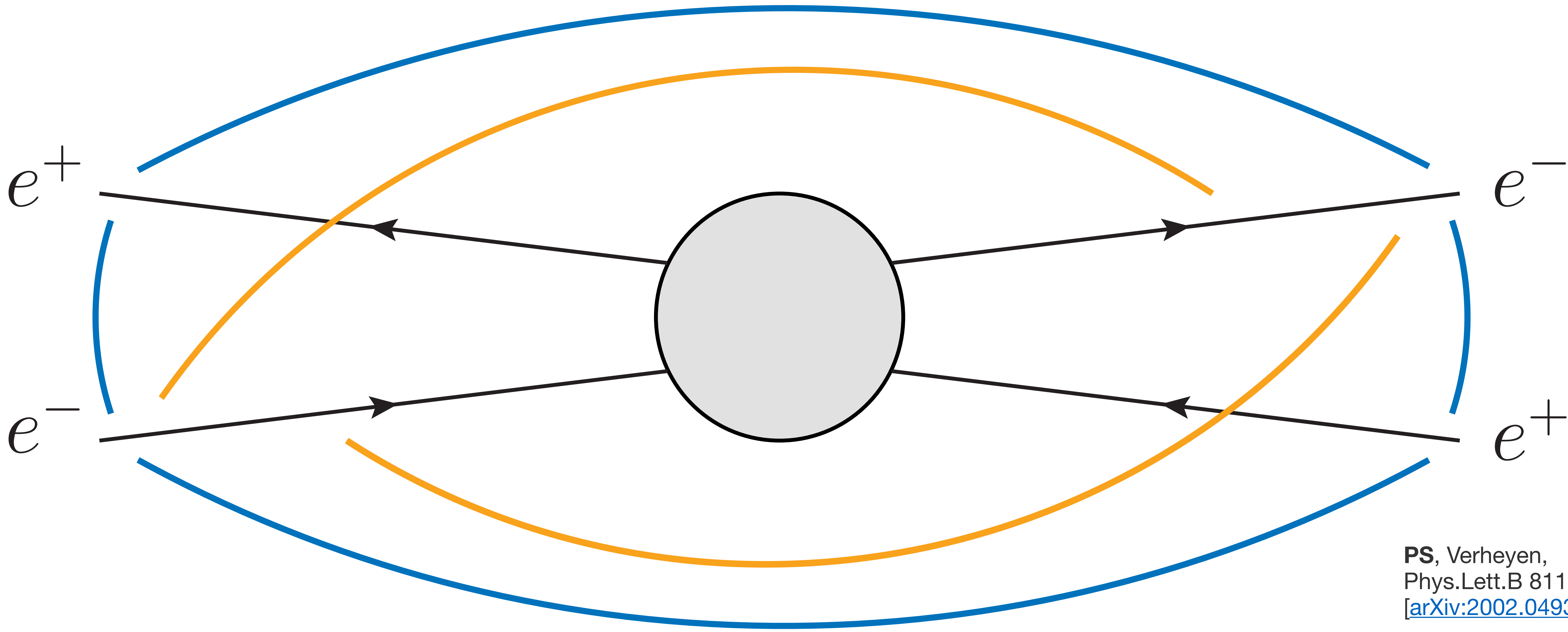
The orange terms are negative ➤ negative weights (+ big cancellations)

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***.